Tropical Connections

South Florida's marine environment

William L. Kruczynski and Pamela J. Fletcher, Editors

Tropical Connections

South Florida's marine environment

William L. Kruczynski and Pamela J. Fletcher, Editors

Preferred citation
Kruczynski, W.L. and P.J. Fletcher (eds.). 2012. Tropical Connections: South Florida's marine environment. IAN Press, University of Maryland Center for Environmental Science, Cambridge, Maryland. 492 pp.

ISBN 978-0-9822305-3-4
First published in 2012
Set in Myriad Pro
IAN Press is committed to producing practical user-centered communications that foster a better understanding of science and enable readers to pursue new opportunities in research, education, and environmental problem solving. IAN Press is the publication division of the Integration and Application Network at the University of Maryland Center for Environmental Science (UMCES). Visit www.ian.umces.edu for information on the publications and access to downloadable reports, newsletters, posters and presentations. Contact IAN Press at ianpress@umces.edu.

PO Box 775
Cambridge, Maryland 21613
U.S.A.
www.ian.umces.edu
ianpress@umces.edu

Disclaimer
This publication was supported by the United States Environmental Protection Agency and the National Sea Grant College Program of the United States Department of Commerce's National Oceanic and Atmospheric Administration. The views expressed are those of the authors and do not necessarily reflect the view of these organizations. The information in this book was current at the time of publication. While the book was prepared with care by authors, IAN Press and the editors accept no liability from any matters arising from its contents. Additional copies are available by contacting IAN Press at http://ian.umces.edu/press/.

The following agencies and organizations also contributed support for the production of this publication. The views expressed in the publication do not necessarily reflect the view of these agencies and organizations and they accept no liability from any matters arising from its contents.

Florida Department of Health
Florida Fish and Wildlife Conservation Commission
Florida International University Foundation
Florida Keys Environmental Fund
Florida Keys National Marine Sanctuary
Florida Sea Grant
Friends and Volunteers of Refuges
National Oceanic and Atmospheric Administration
National Park Service
National Wildlife Refuge System
Protect Our Reefs
Sanctuary Friends Foundation of the Florida Keys
United States Fish and Wildlife Service
University of Florida
University of Maryland Center for Environmental Science
Wildlife Foundation of Florida

Cover images: NASA satellite view of south Florida courtesy of Chuanmin Hu (University of South Florida). Bottom images: mangroves (NOAA), seagrass (Justin Campbell, Florida International University), coral reef (Michael White, NOAA).

Tropical Connections

South Florida's marine environment

Editors
William L. Kruczynski[1] and Pamela J. Fletcher[2]
[1]US Environmental Protection Agency
[2]Florida Sea Grant and the National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory

Science communication
University of Maryland Center for Environmental Science
Integration and Application Network staff:
Kris Beckert, Catherine Bentsen, Tim Carruthers, Bill Dennison, Alexandra Fries, Jane Hawkey, Ben Longstaff, Emily Nauman, Sara Powell, Tracey Saxby, Jane Thomas, Joanna Woerner, and Caroline Wicks.

Administrative staff
Ken Barton, Erica Kropp, and Dorothy Samonisky

Diagrams
Symbols courtesy of the Integration and Application Network (ian.umces.edu/symbols/), University of Maryland Center for Environmental Science

Acknowledgements

We sincerely thank all of the scientists who participated in the discussions that led to the development and organization of this book. We also thank the scientists who contributed text, photographs, and illustrations that are included on these pages. Their expertise and dedication to this project were essential to its completion.

We also thank the skilled science communicators at the University of Maryland Center for Environmental Science for their encouragement, guidance, and for their production of the wonderful illustrations. We feel that their diagrams add immeasurably to the ability to understand and appreciate scientific facts, ecological links, and processes.

We give special thanks to Elizabeth "Libby" Johns and Barbara H. Lidz; their careful editing significantly improved the manuscript.

Finally, we thank our families for their understanding of our dedication to this project and for the many sacrifices that they made that allowed us to complete this book.

André and Alexis, thank you for exploring south Florida's habitats with us and for sharing your photographs of these spectacular resources. South Florida's natural areas are yours to cherish and enjoy. We hope you teach others about this amazing place that is so much a part of you.

This project was funded in part by the "Protect Our Reefs" speciality license plate. By purchasing a Protect Our Reefs license plate, Florida drivers help protect coral reefs and support coral reef research, conservation and outreach programs throughout the state. For more information, visit www.mote.org/4reef

Dedication

We dedicate this book in memory of Brian D. Keller (1949-2010), Science Coordinator, Southeast Atlantic, Gulf of Mexico, and Caribbean Region, the National Oceanic and Atmospheric Administration Office of National Marine Sanctuaries. Brian was a strong supporter for the development of this book and participated in many meetings and discussions that helped frame its form and content. With his passing, coral reef ecosystems around the world have lost a knowledgeable and strong advocate who worked tirelessly to understand these systems so that they can be better protected and conserved, and we have lost a dear and true friend.

Two historic figures in the American environmental movement also stand out as informed and outspoken critics of the consequences of environmental degradation and proponents of the importance of conservation and restoration of natural habitats for the enjoyment by future generations. We also dedicate this book to Rachel Carson (1907 – 1964) and Marjory Stoneman Douglas (1890 – 1998), whose writings taught humankind about the wonder and beauty of the living world. Both recognized the need to educate the public about the connectivity between biological and physical/chemical components of the south Florida marine ecosystem and the importance of conservation of its fragile and limited biological treasures.

Authors

Dala Al-Abdulrazzak
University of British Columbia
Vancouver, British Columbia, Canada

Eric R. Annis
Hood College
Frederick, Maryland

Jerald S. Ault
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Christian L. Avila
Miami-Dade County
Miami, Florida

Andrew C. Baker
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Ken Banks
Broward County
Plantation, Florida

Timothy Banks
Florida Department of Environmental Protection
Tallahassee, Florida

Erich Bartels
Mote Marine Laboratory
Summerland Key, Florida

Donald C. Behringer
University of Florida
Gainesville, Florida

Robin Bennett
South Florida Water Management District
West Palm Beach, Florida

Chris Bergh
The Nature Conservancy
Big Pine Key, Florida

Theresa M. Bert
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
St. Petersburg, Florida

Rodney D. Bertelsen
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Stephen Blair
Miami-Dade County
Miami, Florida

James A. Bohnsack
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Miami, Florida

Joseph N. Boyer
Florida International University
Southeast Environmental Research Center
Miami, Florida

Henry O. Briceño
Florida International University
Southeast Environmental Research Center
Miami, Florida

Joan Browder
National Marine Fisheries Service
Miami, Florida

Mark J. Butler IV
Old Dominion University
Norfolk, Virginia

Thomas P. Carsey
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

Billy D. Causey
National Oceanic and Atmospheric Administration
Office of National Marine Sanctuaries
Key West, Florida

Adam Chasey
Audubon of Florida
Tavernier, Florida

Michael S. Cherkiss
University of Florida
Fort Lauderdale, Florida

Alice Clarke
National Park Service
Everglades National Park
Homestead, Florida

Clayton B. Cook
Florida Atlantic University
Harbor Branch Oceanographic Institute
Fort Pierce, Florida

Carlos A. Coronado
South Florida Water Management District
West Palm Beach, Florida

Carrollyn Cox
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Kevin M. Cunniff
South Florida Water Management District
West Palm Beach, Florida

Steven E. Davis III
Texas A&M University
College Station, Texas

Gabriel A. Delgado
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Nancy Diersing
National Oceanic and Atmospheric Administration
Florida Keys National Marine Sanctuary
Key Largo, Florida

Kevin Dillon
Gulf Coast Research Laboratory
Ocean Springs, Mississippi

Jon Dodrill
Florida Fish and Wildlife Conservation Commission
Division of Marine Fisheries Management
Tallahassee, Florida

Neal M. Dorst
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

Michael J. Durako
University of North Carolina at Wilmington
Wilmington, North Carolina

Karen Dyer
Audubon of Florida
Tavernier, Florida

Dave Eaken
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Holly Edwards
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
St. Petersburg, Florida

Victor Engel
National Park Service
Everglades National Park
Homestead, Florida

Laura Engleby
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
St. Petersburg, Florida

David W. Evans
National Oceanic and Atmospheric Administration
Center for Coastal Fisheries and Habitat Research
Beaufort, North Carolina

Sharon M. L. Ewe
Ecology and Environment, Inc.
West Palm Beach, Florida

Alicia Farrer
Florida Department of Environmental Protection
Florida Keys National Marine Sanctuary
Key West, Florida

Jack W. Fell
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

M. Drew Ferrier
Hood College
Frederick, Maryland

William K. Fitt
University of Georgia
Athens, Georgia

Bryan Fluech
Florida Sea Grant
Naples, Florida

James W. Fourqurean
Florida International University
Southeast Environmental Research Center
Miami, Florida

Thomas A. Frankovich
Florida International University
Southeast Environmental Research Center
Key Largo, Florida

Sara Frias-Torres
Ocean Research and Conservation Association
St. Petersburg, Florida

J. Carrie Futch
University of Georgia
Athens, Georgia

Piero R. Gardinali
Florida International University
Miami, Florida

George Garrett
City of Marathon
Marathon, Florida

David S. Gilliam
Nova Southeastern University
Oceanographic Center
Fort Lauderdale, Florida

Robert A. Glazer
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Patricia M. Glibert
University of Maryland
Center for Environmental Science
Cambridge, Maryland

William Goodwin
National Oceanic and Atmospheric Administration
Florida Keys National Marine Sanctuary
Key Largo, Florida

Lewis J. Gramer
University of Miami
Cooperative Institute for Marine and Atmospheric Studies
Miami, Florida

Dale W. Griffin
United States Geological Survey
Tallahassee, Florida

Margaret O. Hall
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
St. Petersburg, Florida

Pamela Hallock
University of South Florida
College of Marine Science
St. Petersburg, Florida

Meghan Harber
Key West, Florida

Kristen Hart
United States Geological Survey
Davie, Florida

Rebecca G. Harvey
University of Florida
Fort Lauderdale, Florida

Cynthia Heil
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
St. Petersburg, Florida

Michael R. Heithaus
Florida International University
Miami, Florida

James C. Hendee
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

Jeanette F. Hobbs
Audubon of Florida
Marathon, Florida

Chuanmin Hu
University of South Florida
College of Marine Science
St. Petersburg, Florida

John H. Hunt
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Walter C. Jaap
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
St. Petersburg, Florida

Elizabeth Johns
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

Grace M. Johns
Hazen and Sawyer
Hollywood, Florida

Jocelyn L. Karazsia
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
West Palm Beach, Florida

Christopher Kelble
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

Brian D. Keller
National Oceanic and Atmospheric Administration
Office of National Marine Sanctuaries
St. Petersburg, Florida

Stephen P. Kelly
South Florida Water Management District
West Palm Beach, Florida

Kiho Kim
American University
Washington, District of Columbia

Marguerite Koch
Florida Atlantic University
Boca Raton, Florida

Villy H. Kourafalou
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Christopher Langdon
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

James J. Leichter
Scripps Institution of Oceanography
La Jolla, California

Thomas N. Lee
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Stephanie Leeds
Florida Department of Environmental Protection
Tallahassee, Florida

Cynthia F. Lewis
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Barbara H. Lidz
United States Geological Survey
St. Petersburg, Florida

Stephen R. Lienhart
URS Corporation
Tampa, Florida

Erin K. Lipp
University of Georgia
Athens, Georgia

Diego Lirman
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Thomas E. Lodge
Thomas E. Lodge Ecological Advisors, Inc.
Coral Gables, Florida

Jerome J. Lorenz
Audubon of Florida
Tavernier, Florida

Lauri MacLaughlin
National Oceanic and Atmospheric Administration
Florida Keys National Marine Sanctuary
Key Largo, Florida

Christopher J. Madden
South Florida Water Management District
West Palm Beach, Florida

Geofrey Mansfield
Florida Department of Environmental Protection
Tallahassee, Florida

Frank E. Marshall
Cetacean Logic Foundation, Inc.
New Smyrna Beach, Florida

Kerry E. Maxwell
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Frank J. Mazzotti
University of Florida
Davie, Florida

Scott McClelland
Camp, Dresser & McKee, Inc.
Tampa, Florida

Loren E. McClenachan
Simon Fraser University
Burnaby, British Columbia, Canada

Amanda A. McDonald
South Florida Water Management District
West Palm Beach, Florida

Maia McGuire
Florida Sea Grant
Bunnell, Florida

Fred McManus
United States Environmental Protection Agency
Atlanta, Georgia

Anne McMillen-Jackson
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
St. Petersburg, Florida

Guy H. Means
Florida Department of Environmental Protection
Florida Geological Survey
Tallahassee, Florida

Nelson Melo
University of Miami
Cooperative Institute for Marine and Atmospheric Studies
Miami, Florida

Gary R. Milano
Miami-Dade County
Miami, Florida

Margaret W. Miller
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Miami, Florida

Steven L. Miller
University of North Carolina at Wilmington
Key Largo, Florida

Martin A. Moe, Jr.
Mote Marine Laboratory
Summerland Key, Florida

Anne Morkill
United States Fish and Wildlife Service
Florida Keys National Wildlife Refuges
Big Pine Key, Florida

Jonathan G. Moser
National Park Service
South Florida/Caribbean Network
Miami, Florida

Douglas Morrison
National Park Service
Dry Tortugas National Park
Homestead, Florida

Erich M. Mueller
Perry Institute for Marine Sciences
Lee Stocking Island
Exuma, Bahamas

William K. Nuttle
Eco-hydrology
Ottawa, Ontario, Canada

John H. Paul
University of South Florida
College of Marine Science
St. Petersburg, Florida

Joseph R. Pawlik
University of North Carolina at Wilmington
Wilmington, North Carolina

Larry Perez
National Park Service
Everglades National Park
Homestead, Florida

Esther C. Peters
George Mason University
Fairfax, Virginia

Richard H. Pierce
Mote Marine Laboratory
Sarasota, Florida

James W. Porter
University of Georgia
Athens, Georgia

Jessica Powell
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
St. Petersburg, Florida

Ellen Prager
Aquarius Reef Base
Key Largo, Florida

Lindsey L. Precht
Williams College
Williamstown, Massachusetts

William F. Precht
National Oceanic and Atmospheric Administration
Florida Keys National Marine Sanctuary
Key Largo, Florida

Gus Rios
Florida Department of Environmental Protection
Marathon, Florida

Kim B. Ritchie
Mote Marine Laboratory
Sarasota, Florida

Victor H. Rivera-Monroy
Louisiana State University
Baton Rouge, Louisiana

Michael B. Robblee
United States Geological Survey
Homestead, Florida

Michelle Robinson
Audubon of Florida
Tavernier, Florida

David T. Rudnick
South Florida Water Management District
West Palm Beach, Florida

Darren G. Rumbold
Florida Gulf Coast University
Fort Myers, Florida

Rob Ruzicka
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
St. Petersburg, Florida

Deborah L. Santavy
United States Environmental Protection Agency
Gulf Ecology Division
Gulf Breeze, Florida

Joseph E. Serafy
National Oceanic and Atmospheric Administration
National Marine Fisheries Service
Miami, Florida

David A. Score
National Oceanic and Atmospheric Administration
Marine Operations Center-Atlantic
Norfolk, Virginia

Jeffrey D. Shields
Virginia Institute of Marine Science
Gloucester Point, Virginia

Eugene A. Shinn
Unites States Geological Survey
St. Petersburg, Florida

Ned Smith
Florida Atlantic University
Harbor Branch Oceanographic Institute
Fort Pierce, Florida

Struan R. Smith
Georgia State University
Atlanta, Georgia

Ryan H. Smith
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

Thomas J. Smith III
United States Geological Survey
St. Petersburg, Florida

Jack Stamates
National Oceanic and Atmospheric Administration
Atlantic Oceanographic and Meteorological Laboratory
Miami, Florida

John Stevely
Florida Sea Grant
Palmetto, Florida

Mac Stone
Audubon of Florida
Tavernier, Florida

Kathryn Patterson Sutherland
Rollins College
Winter Park, Florida

Peter K. Swart
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Don Sweat
Florida Sea Grant
Gainesville, Florida

Richard Tanner
City of Marathon
Marathon, Florida

Jack Teague
Finatic Charters
Key West, Florida

Marie-Agnès Tellier
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Max Teplitski
University of Florida
Gainesville, Florida

Robert R. Twilley
Louisiana State University
Baton Rouge, Louisiana

Jeremy J. Vaudo
Florida International University
Miami, Florida

David Vaughan
Mote Marine Laboratory
Summerland Key, Florida

John D. Wang
University of Miami
Rosenstiel School of Marine and Atmospheric Science
Miami, Florida

Harold Wanless
University of Miami
Miami, Florida

Ryan Wattam
National Oceanic and Atmospheric Administration
Florida Keys National Marine Sanctuary
Key Largo, Florida

Kevin R. T. Whelan
National Park Service
South Florida/Caribbean Network
Miami, Florida

Renee Wilson
Rookery Bay National Estuarine Research Reserve
Naples, Florida

G. Lynn Wingard
United States Geological Survey
Reston, Virginia

Erin Woods
Audubon of Florida
Tavernier, Florida

Adrianna Zito
Florida Fish and Wildlife Conservation Commission
Fish and Wildlife Research Institute
Marathon, Florida

Image contributors

Adams J, advancedaquarist.com
Anderson C, USFWS
Anderson J, NOAA
Anderson K, lighthousefriends.com
Archie Mayor Collection
Averette M
Ault JS, UM/RSMAS
Avila C, Miami-Dade County Department of Environmental Resources Management (DERM)
Bailey H, FKNMS
Baker AC, UM/RSMAS
Bartels E, Mote Marine Laboratory
Battle K, Biscayne National Park
Behringer DC, University of Florida
Benvenuti L
Bertelsen RD, FWC
Booher A, Federal Emergency Managment Agency
Bortone SA, Gulf Coast Marine Fisheries Commission (GCMFC)
Bourque A, NPS
Brown-Peterson N, University of Southern Mississippi (USM)
Bruckner A, NOAA
Burdick D, NOAA
Butler IV MJ, Old Dominion University (ODU)
Butler R
Campoli B, National Undersea Research Center (NURC)
Carman H, SFWMD
Carruthers T, Integration and Application Network (IAN) Image Library
Charpin F, reefguide.org
Cook CB, Harbor Branch Oceanographic Institute (HBOI)
Cox C, FWC
Crewz DW, FWRI
D'Alessandro E, UM/RSMAS
DeMaria D
Deskpictures.com
Dine H, FKNMS
Dodge R, Nova Southeastern University (NSU)
Dolphin Ecology Project
dolphindreamteam.com
Durako MJ, University of North Caroline-Wilmington (UNCW)
Everglades National Park (ENP)
Ewe SML, ENE
Fajans J, Florida Institute of Oceanography (FIO)
Farrer A, FKNMS
Feingold J, NOAA
Fell JW, UM/RSMAS
Fitt WK, University of Georgia (UGA)
Fitzgerald M
Fletcher PJ, Florida Sea Grant (FSG)
Florida Bay Fisheries Habitat Assessment Program (FHAP)
Florida Department of Environmental Protection (FDEP)
Florida Department of Health
Florida Department of Transportation (FDOT)
Florida Division of Library and Information Services
Florida Fish and Wildlife Conservation Commission (FWC)
Florida Fish and Wildlife Research Institute (FWRI)
Florida Keys National Marine Sanctuary (FKNMS)
Florida Keys Public Libraries
Fluech B, FSG
Ford P, Pat Ford Photography
Frankovich TA, Florida International University (FIU)
Freeley M, FWRI
Friends of the Loxahatchee National Wildlife Refuge
Gillette P, UM/RSMAS
Gilliam DS, NSU
Gonzales J
Goodwin W, FKNMS
Google Earth
Griffin DW
Guzman W, University of Miami (UM)
Hall MO, FWRI
Hallock P, University of South Florida (USF)
Hammerschlag N, UM/RSMAS neilhammer.com
Hernkind WF, Florida State University (FSU)
Hinson T
Historical Preservation Society of the Upper Keys, keyshistory.org
Howard RA, Smithsonian Institution
Hu C, USF
Industrial Economics, Inc.
Jackson TL, National Marine Fisheries Service (NMFS)
Jaap WC, FWRI
Johns Hopkins University
Johnson M, TNC
Kang HS, UM/RSMAS
Kelble C, NOAA
Kendall C, Society for Sedimentary Geology (SEPM)
Keys Environmental Restoration Fund
Key West Citizen
Koch M, Florida Atlantic University (FAU)
Killam K, USFWS
Kruczynski WL, Environmental Protection Agency (EPA)
Lewis C, FWC
Library of Congress
Lipp E, UGA
Lirman D, UM/RSMAS
Littler DS
Littler MM
Luo J, UM/RSMAS
Lupo Dion R, sharksavers.org
MacDiarmid A, FWC
MacLaughlin L, FKNMS
MACTEC
Marino J
Massey A, FKNMS
Matz M, University of Texas (UT)
McClenachan LE, Simon Fraser University (SFU)
McGuire M, FSG
Millie K, FWC
Moe Jr MA, Mote Marine Laboratory (MML)
Molina Fletcher AM
Molina R
Monroe County Public Library
Morris L, St. Johns River Water Management District (SJRWMD)
Morrison D, NPS
Mueller EM, MML
Muenzer C
Mulrooney B
Myhre L, Creative Commons
National Academy of Science Archives
National Aeronautics and Space Administration (NASA)
National Park Service (NPS)
National Oceanic and Atmospheric Administration (NOAA)
Nedimyer K, Coral Restoration Foundation (CRF)
Noyes T
O'Malley M, sharksavers.org
Pawlik J, UNCW
Peters EC, George Mason University (GMU)
Perez L, NPS
Phillips RC
Porter JW, UGA
Precht WF, FKNMS
Richie KB, MML
Rivera-Monroy VH, Louisiana State University (LSU)
Rochford M, UF
Rogers C, USGS
Roller DJ, NURC
Rookery Bay National Estuarine Research Reserve
Rose C, Seagrass Ecosystem Research Laboratory FIU
Ruzicka R, FWRI
Santavy DL, EPA
Schmahl GP, NOAA
Scott T, Florida Geological Survey (FGS)
Sea Around Us Project
Seagrass Ecosystem Research Laboratory, FIU
Sheppard C and A, coralpedia.bio.warwick.ac.uk
Shinn EA, USGS
Smith P
Smith III TJ, USGS
South Florida Water Management District (SFWMD)
Spadaro J, UF
Spring S, Palm Beach County Reef Rescue
Stamates J, NOAA
Stone M, Mac Stone Photography
Swart PK, UM/RSMAS
Teague J, Finatic Charters
Twilley RR, LSU
The Nature Conservancy (TNC)
Uhrin AV, NOAA
United States Fish and Wildlife Service (USFWS)
United States Geological Survey (USGS)
University of Miami/Rosenstiel School of Marine and Atmsospheric Science (UM/RSMAS) Cooperative Unit for Fisheries Education and Research (CUFER)
Ward M, NURC
White M, FKNMS
Wikimedia
Wil-Art Studio
Wilmers T, USFWS
Wisniewki M
Wolny J, FWC
Woods Hole Oceanographic Institution (WHOI)
Wylie Jr AS, Cabot Oil and Gas Exploration (COGE)
Ziegler T, NPS

Contents

About this book

We prepared this book to summarize technical information on the south Florida marine ecosystem in a manner that is easy to read and understand. The target audiences of the book are students, educators, lay readers, and decision makers. The information presented in this book will further the understanding and appreciation of this diverse and complex ecosystem, correct any misconceptions about facts or ecological processes, and promote conservation and management decisions that are based upon sound, defensible scientific findings.

The book is unique in that it consists of fact pages that were prepared by 162 experts in their scientific disciplines. The fact pages can be used individually, but they are also organized into chapters that synthesize the information. Chapter introductions summarize and supplement information given in the chapter and sources are footnoted. Scientific citations are not included on the fact pages in order to make the text flow better for the targeted audiences. An annotated list of further readings is included at the end of each chapter. We had no intention of representing the thoughts and knowledge of others as our own in the introductions to the chapters or any place else in this book.

We anticipate that there will be several levels of readers of this book. Some will read every word, while others may browse through the pages. It is possible that the browsers may not completely receive the main messages of the book because they are spread across its chapters and pages. So, we are stating the main messages of the book explicitly here.

- South Florida is the lower portion of the Florida peninsula south of latitude 27. This area represents the southern limit of many temperate organisms and the northern limit of many tropical organisms, resulting in the amazing biodiversity of life forms in the area.

- The hydrology of south Florida is complex due to the influences of currents from the Caribbean Sea, Gulf of Mexico, and the Atlantic Ocean. It is an area of convergence of external influences and important internal circulation patterns, and both function to maintain biodiversity and populations of the flora and fauna.

- The marine environments discussed in this book include shallow-water habitats of the Atlantic Ocean and the Gulf of Mexico to the edge of the continental shelf, coastal bays and estuaries, and adjacent wetlands, including mangrove forests. All of these habitats are physically and biologically connected, and all are critical elements of the entire south Florida marine ecosystem. In order to maintain or restore the ecosystem, wise management of all components of the ecosystem is required.

- The human population of south Florida is growing. Declining water quality, physical damage to coral reefs, seagrass beds, mangrove forests, and decreased fish landings are symptoms of increasing impacts by humans to the south Florida marine ecosystem.

- Impacts to the ecosystem occur at local, regional, and global scales, and solutions must operate at all scales to be effective.

- In order to restore and maintain the marine ecosystem, we must first understand its complexity and the connectivity between aquatic habitats, and promote wise management based upon that understanding. Citizens play an important role in fostering and implementing conservation and restoration practices.

We titled this book "Tropical Connections" for several reasons. Classically, the tropics are located at latitudes near the equator, between the Tropic of Cancer (23.4° N) and the Tropic of Capricorn (23.4° S), and by that definition south Florida (about 25° N) is "subtropical." However, "tropical" can be used in a general sense to mean warm to hot and moist year-round conditions with lush vegetation. The southern Florida mainland and the Florida Keys meet that latter definition and support a prevalence of vegetation derived from the Caribbean tropics, including many species of palms and Caribbean tropical hardwood trees. The growth and survival of tropical plant species in south Florida are better near the coast because of the warming influence of the Florida Current and coastal waters. It is this maritime influence that allows tropical plants and animals to survive north of the Tropic of Cancer.

The title contains the word "connections" because the marine habitats of south Florida are interconnected physically, chemically, and biologically, as well as connected with other geographic areas. If you live, vacation, boat, swim, snorkel, SCUBA dive, fish, spear fish, bird watch, or eat marine fish or shellfish in south Florida, you are "connected" to the south Florida marine habitats. Also, people who read about, study, or enjoy knowing that the marine habitats of south Florida exist as natural wonders have a special connection to this place that may be no less significant than physical experiences.

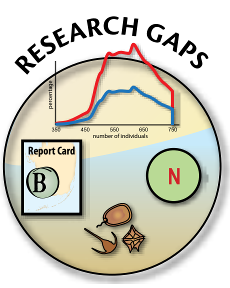
The synthesis of information contained in this book will result in an appreciation and understanding of this resource and will support conservation and management measures that will allow future generations the opportunity to share and enjoy its richness and beauty. We sincerely hope that you enjoy this book and find it useful.

Bill and Pamela

1. GEOGRAPHIC SETTING AND IMPACTS TO THE ENVIRONMENT

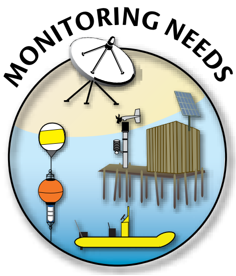
Geographic Setting and Impacts to the Environment Chapter Recommendations

- Recognize the vulnerability and impacts on south Florida marine habitats that are located adjacent to city centers and develop measures to **reduce local sources of pollution**.
- Identify and prioritize the **causes of ecosystem declines** and implement management actions to address and reverse the declines.
- Recognize the impacts of **global climate change** and sea-level rise in planning processes, and identify ways to reduce the local contributions to greenhouse gases.
- Include impacts from **farfield sources** to south Florida in planning.
- Promote the value of **ecosystem services** that benefit the south Florida economy and quality of life, such as tourism dollars generated from visitation to parks and natural areas, and incorporate those elements in regional and local planning.
- Apply the concepts of **"carrying capacity" and "smart growth"** to management decisions affecting the natural and "built" environments in south Florida.



- Conduct targeted research to separate ecosystem responses to **natural variability** from those caused by anthropogenic stresses.
- Further quantify the effects of **global warming and ocean acidification** to facilitate accurate predictions and to design appropriate management strategies and actions.
- Investigate the impacts of **African dust** on productivity of waters and public health in controlled laboratory experiments to improve the understanding of those impacts and determine how resource management and planning can minimize or reverse the impacts.
- Clarify the effect of the **elimination of top predator species** on ecosystem structure and function to facilitate setting scientifically defensible resource management goals.
- Quantify the effects of existing roadbeds and causeways that **impede flushing rates** and affect biological populations in coastal waterways.
- Identify parameters to rapidly **assess ecosystem health**.

Chapter title page: Hurricane Andrew approaching Florida (1992). NOAA.



- Develop and support monitoring programs required to assess **long-term impacts of episodic (infrequent) events**, such as tropical storms, shifts in ocean currents, and African dust.
- Design monitoring programs to **detect environmental changes** to support defensible management actions.
- Use effective and efficient monitoring methods, such as **remote sensing**, to provide broad-scale geographic evaluations that can be used to assess local, regional, and global conditions.
- Investigate the utility of developing a comprehensive water quality monitoring program along the Southwest Florida Shelf to provide an **early warning** of movement of pollutants or other adverse environmental conditions to downstream locales in south Florida to aid managers in planning response actions to environmental perturbations.

J. Luo - UM/RSMAS

Coral reefs provide habitat for a diverse assemblage of marine life in south Florida.

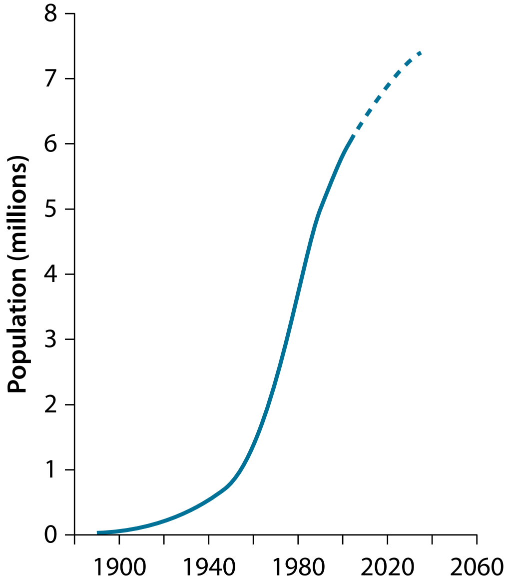
Introduction

The south Florida watershed begins in East Lake Tohopekaliga, Osceola County, and flows south via the Kissimmee River to Lake Okeechobee. Historically, overflow from Lake Okeechobee flowed through the Everglades to coastal areas and south to Florida Bay. This book encompasses those areas of the south Florida marine environments from Martin County on the Atlantic coast to Charlotte County on the Gulf of Mexico coast.

South Florida is a special place to live, work, and play. It is an area where climates, cultures, habitats, biogeography, and ocean currents converge. The mild, subtropical climate allows year-round outdoor activities that are enjoyed by residents and visitors alike. Evidence of south Florida popularity is reflected by the growing population. Palm Beach, Broward, and Miami-Dade Counties accounted for 27% of the overall growth in the State of Florida in the past several years, and the population of Collier County grew 25.4% from 2000 – 2008.[1,2] The resident population of south Florida is

South Florida marine environment is closely linked to upland and upstream influences. This book examines the coastal area from Martin County on the east coast to Charlotte County on the Gulf of Mexico coast.

projected to increase from approximately 4 million in 2004 to 7.2 million in 2035.[3,4,5] Residents of south Florida are a mix of many nationalities that results in a unique and attractive diversity of cultures and entertainment, dining, and recreation. Tourism is a main source of income to the local economy, and approximately 25 million people visit south Florida annually, spending approximately $19 billion.



Adapted from BEBR, UF.

The population of southeast Florida is projected to increase to approximately 7.2 million residents by 2035.

The multitude of natural communities found in south Florida is part of its uniqueness and allure. The resources are a diverse mix of upland, wetland, and aquatic habitats that include hardwood hammocks, mangrove communities, coastal lagoons and bays, and coral reefs and hardbottoms. Many consider the beaches of south Florida unparalleled in their beauty. The Florida Everglades is one of only three sites on Earth declared an International Biosphere Reserve, a World Heritage Site, and a Wetland of International Importance.[6,7] The Everglades offer many recreational opportunities, including bird watching, hiking, camping, boating, fishing, and exploring nature. Mangrove forests protect natural shorelines and provide habitat for birds and fish. Seagrass meadows abound in shallow, clear marine waters, and the seagrass area in south Florida is the most expansive documented seagrass bed on Earth.[8] Seagrasses support a diversity of life, including recreational and commercial species of fish. South Florida is the only place in the continental United States where one can visit a tropical coral reef or hardbottom habitat by boat or by swimming from shore.

The flora and fauna of south Florida are an interesting and unique mix of tropical and temperate species, many at the geographic limits of their range. On land, pineland forests, tropical hardwood hammocks, sawgrass marshes, cypress swamps, and rockland communities exist in a mosaic of diverse habitats. In marine environments, biogeographic provinces describe assemblages of life adapted to particular geographic areas. In south Florida, organisms from the Carolinian, Louisianian, and West Indian biogeographic provinces live together and result in a biodiversity "hot spot." For example, more than 500 species of fish live in the coastal waters of south Florida.

W. L. Kruczynski - EPA

Beaches of south Florida attract millions of visitors each year.

Native American hunter-gatherers visited and occupied south Florida as early as 10,000 years ago and thrived on deer, bear, waterfowl, and the bounties of the sea. European explorers and slave hunters began arriving in the early 1500s. Juan Ponce de León was the first

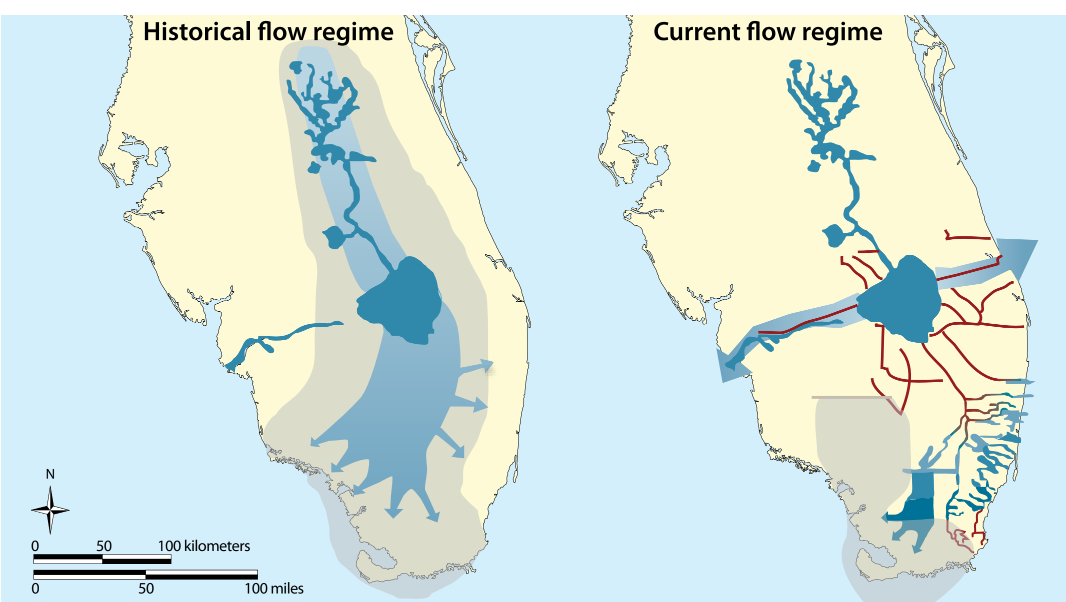
European to see the Miami area when he sailed into Biscayne Bay. At that time, freshwater springs in Biscayne Bay were a source of freshwater for sailing ships. Similar freshwater springs were reported in Florida Bay. In the short time span of approximately 250 years, Native Americans were all but eliminated from the area by swords, guns, disease, rum, and pitting of Indian nations against one another.[9] Taming the land by white settlers did not come easily, but eventually limiting factors were overcome: marshes and swamps were drained and converted to agriculture, mosquito populations carrying yellow fever and malaria were reduced, and refrigeration and air conditioning were invented.

Growth along the east coast of south Florida focused on conversion of Everglades wetlands to agriculture and, subsequently, to housing and industrial developments. Rock mines were constructed to obtain fill material for roads and other development requiring

Wikimedia

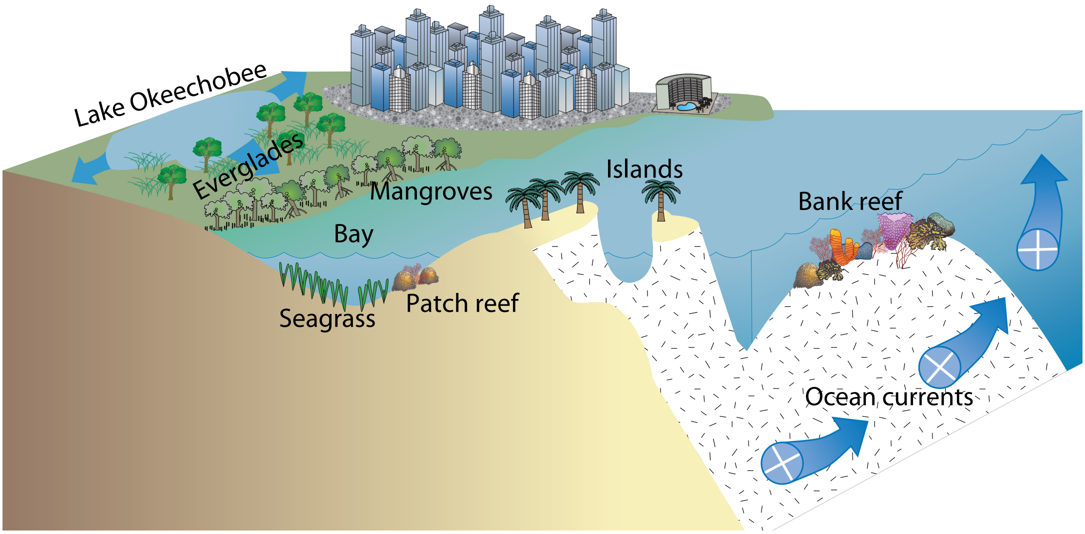
In 1907, the State of Florida established the Everglades Drainage District to "drain the abominable pestilence-ridden swamp." Construction of a network of drainage ditches, such as the one shown (ca. 1915), allowed the conversion of large portions of the Everglades to agricultural lands.

an increase in elevation to reduce the effects of seasonal flooding. In 1907, the construction of a vast network of inland drainage canals was initiated, and by 1928, the American winter vegetable kingdom was fashioned from the Everglades.[10] With plentiful crops, beef, and dairy products assured, the stage was set for the metropolitan and industrial expansion that characterizes south Florida



SFWMD

Historical (left) and current (right) freshwater flows in the south Florida watershed. Removal of water through a vast system of drainage canals (red lines in right image) converted wetlands into areas suitable for farming and land development and reduced the danger of flooding to low-lying development. It also dried out the Everglades and resulted in increased salinities in Florida Bay and Biscayne Bay and decreased salinities in the St. Lucie and Caloosahatchie estuaries.



The southern portion of the Florida peninsula includes: sawgrass prairies, mangrove-fringing shorelines, bays, seagrass meadows, islands, exposed relict reef, patch reefs, bank reefs, hardbottom habitats, and blue-water environments.

today.[11] Drainage of "excess" freshwater to the sea through the vast system of canals not only allowed conversion of large areas of the Everglades to agriculture, but also significantly altered the historical flow of freshwater to Biscayne Bay and Florida Bay. Rapid drainage also decreased the amount of freshwater that seeps into underground aquifers, which resulted in the reduction and the disappearance of freshwater springs in Biscayne Bay and Florida Bay.

Dense human populations living along a relatively narrow coastal strip in south Florida and the Florida Keys eventually led to additional conflicts between the growing population and natural communities as well as among various user groups. These conflicts were due to overuse of natural resources, such as hunting large wildlife to extinction (e.g., harbor seals) or near extinction (e.g., panthers, alligators), uncontrolled harvesting of fish and other marine resources (e.g., sea turtles, sharks, sawfish, large grouper, queen conch), and boat collisions with wildlife (e.g., manatees). Additional areas continued to be drained and filled to create more housing for the ever-growing population. Other conflicts were due to misuse of natural resources, such as treating nearshore waters as disposal sites for garbage and untreated stormwater and wastewater; the uncontrolled use of pesticides and other toxic materials; the intentional or accidental release of exotic species; anchoring and boat groundings on corals and seagrasses; and motoring through shallow seagrass meadows, causing long-lived propeller scars. All these examples are symptoms of too many people competing for limited space and resources as well as inadequate management and public awareness.

Global stressors are also impacting the region, including global warming, ocean acidification, hurricane frequency and intensity, and African dust. Sea-level rise is a result of global warming, and its rate is increasing over historical levels. Changes in water levels will have severe impacts in south Florida because of low elevations and dense shoreline development. Rising levels of carbon dioxide in the atmosphere are also causing changes in the acidity of the ocean. Marine organisms with calcium carbonate shells or skeletons rely on dissolved minerals in seawater. Changing ocean chemistry may decrease the ability of some organisms to effectively grow and reproduce.[12,13]

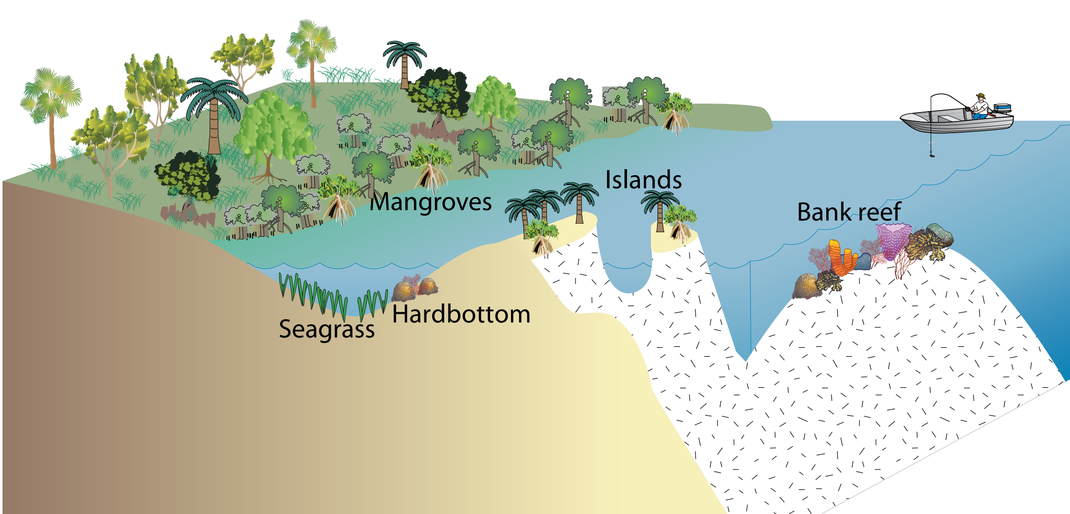
South Florida has many diverse habitats

Thomas E. Lodge

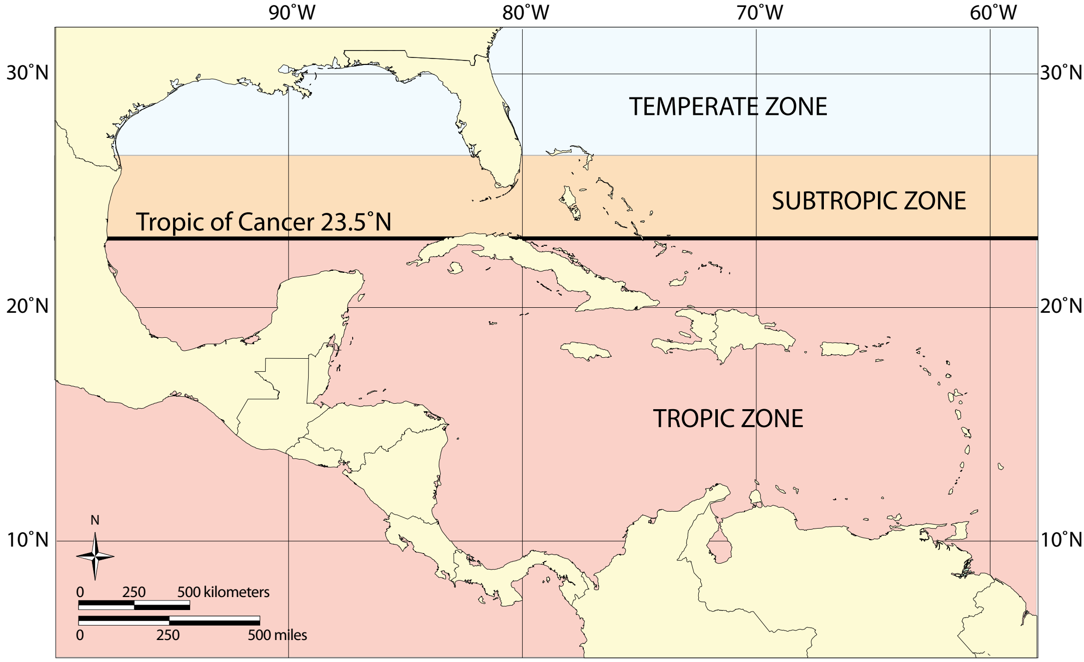
South Florida is the portion of the Florida peninsula from Lake Okeechobee southward through the Florida Keys. This area is unique in many ways. Around the world, at the same latitude as south Florida, there are vast areas of desert, including the Sahara in northern Africa and deserts in western Mexico. Despite being a peninsula of comparable configuration to Florida, Baja California in Mexico is a mountainous desert, whereas Florida has low elevation and high rainfall. The highest land in south Florida is about 12 meters (40 feet) above sea level, but the majority is less than 6 m (20 ft). Annual rainfall averages 130 – 150 centimeters (50 – 60 inches), 60% of which is from thunderstorms and tropical weather events in the warmest 4 months (June – September). Throughout the rainy summer, moisture-laden trade winds arrive from the Atlantic Ocean, resulting in abundant thunderstorms. If the rainfall pattern in south Florida followed that of northern Florida, where frontal-based weather systems bring spring rains and frequent summer droughts, the two large and unique physiographic features of the south Florida mainland—the Everglades and Big Cypress Swamp—would not exist. The abundant summer rainfalls provide a source of freshwater, but much of the historical flow is now intercepted by drainage canals that were constructed for flood control. These have disrupted the timing and distribution of freshwater to coastal areas.

The Florida peninsula extends from the temperate climate portion of North America into the northern limits of the West Indian tropics. In south Florida, tropical species commingle with warm-temperate species. This mixing makes south Florida unique from neighboring tropical marine waters, such as the Bahamas and Cuba, which largely lack the temperate component to their flora and fauna.

The physical and climatic setting of south Florida has resulted in many localized features. Because of the regional low elevations, surface waters move



South Florida is the portion of the Florida peninsula from Lake Okeechobee southward through the Florida Keys. Unique natural habitats include the Everglades, Big Cypress Swamp, Ten Thousand Islands, and tropical coral reefs. Flora and fauna are a unique mix of warm-temperate and tropical species.



South Florida is located along the southern margin of the temperate region of North America and the northern margin of the tropics.

as a shallow "blanket" of water called "sheetflow" across the Everglades and Big Cypress Swamp and not in defined creeks or rivers. Upon reaching coastal areas, the flows collect into countless tidal creeks and small rivers, creating highly productive estuarine habitats.

South Florida coastline includes three additional unique habitats: coral reefs and hardbottom, shallow coastal bays, and the Florida Keys. The Florida Keys comprised fossilized coral reefs and marine sediment deposits that were created during a time of higher sea level. Today, these islands, and the modern coral reefs found seaward of the islands, separate the oceanic environment from the protected shallow coastal environments to the west and northwest, including Florida Bay, Barnes Sound, Card Sound, and Biscayne Bay. Southern Biscayne Bay is loosely enclosed by islands formed of coral reef origin, but its northern portion is separated from the ocean by sand-based islands, Miami Beach and Key Biscayne, that are the southernmost barrier islands on the east coast of Florida.

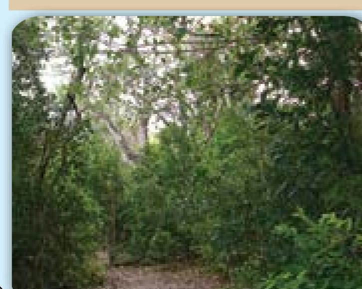
Historically, bays and lagoons landward of the barrier islands benefited from diffuse freshwater flows through mangrove-fringed shorelines and tidal creeks. However, drainage canals have damaged these functions by periodically discharging large pulses of freshwater, which result in wide fluctuations in salinity in these habitats. Redfish (*Sciaenops ocellatus*), formerly common in Biscayne Bay, were apparently eliminated by damage to their nursery grounds shortly after drainage canals were built.

Many changes have been made to the unique habitats of south Florida. The Comprehensive Everglades Restoration Plan is designed to help redistribute canal flows diffusely through coastal mangrove swamps and into nearshore bay communities and increase flows through the entire Everglades system to the south and southwest coast. Biscayne Bay and Florida Bay are especially important recipients of these "restored" flows that should help to reestablish the ecological functions of the diverse habitats in the region.

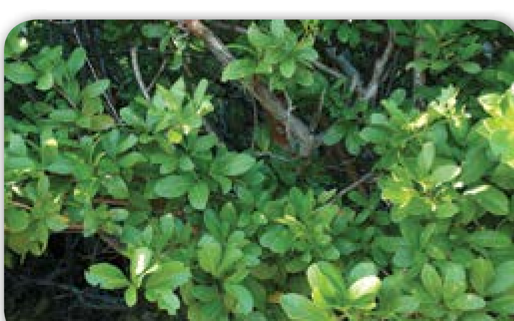
Tropical hardwood hammocks

Pamela J. Fletcher, William L. Kruczynski, and Thomas E. Lodge

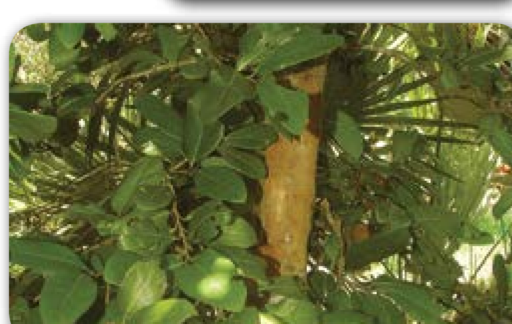
A hammock is an upland area where the ground elevation is high enough to prevent seasonal flooding. A brief discussion of their composition is included here because of their proximity to the marine environment, their important habitat value, and the fact that many acres have been lost or fragmented by coastal development. Hammocks in south Florida, from about Miami southward, are dominated by tropical trees of West Indian origin intermixed with a few temperate species. This plant community was established in south Florida about 6000 years ago during postglacial warming. Tropical hardwood hammocks occur in Everglades National Park, the southern portion of Big Cypress National Preserve, and the Florida Keys as well as along the Atlantic coastline to about Pompano Beach. Only a short distance north, the majority of tropical species, such as Jamaican dogwood (*Piscidia piscipula*), blackbead (*Pithecellobium guadalupense*), gumbo limbo (*Bursera simaruba*), and pigeon plum (*Coccoloba diversifolia*) do not thrive, or are cold-pruned to short stature.



A.M. Molina Fletcher



W.L. Kruczynski - EPA



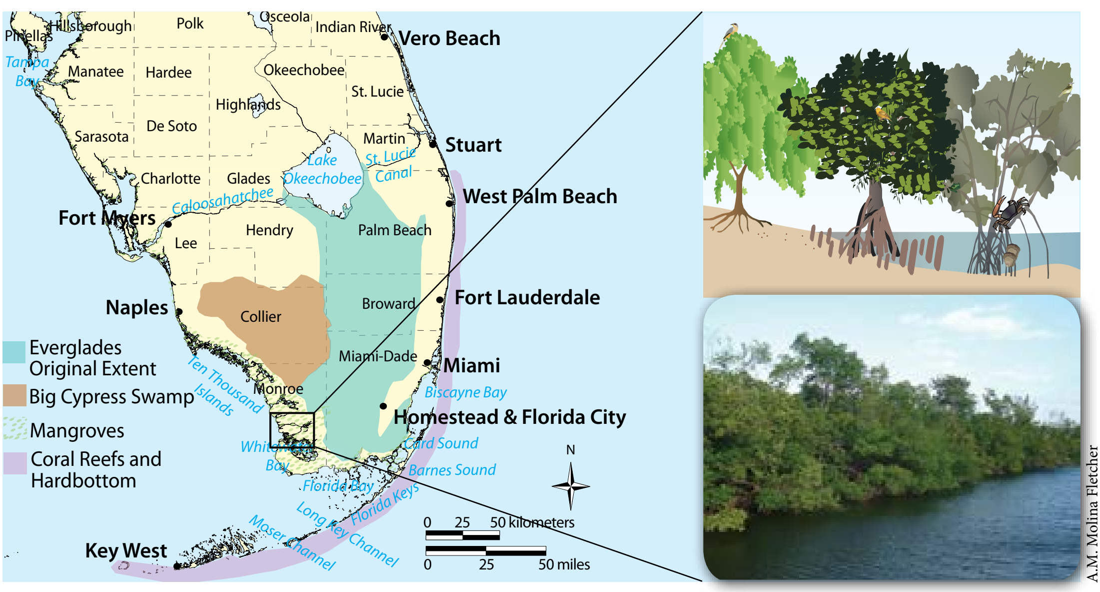
W.L. Kruczynski - EPA

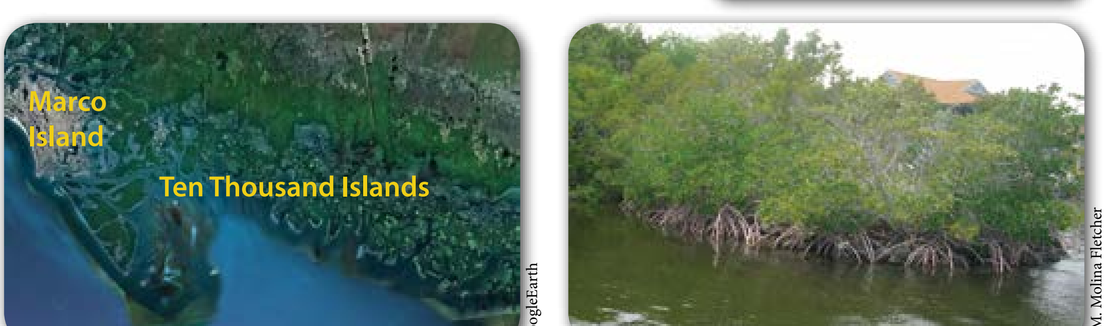
Blackbead (left) and pigeon plum (right) are common tropical hardwood hammock species.

Mangrove communities

Pamela J. Fletcher, William L. Kruczynski, and Thomas E. Lodge

Mangroves in Florida can be found as far north as St. Augustine on the east coast and Cedar Key on the west coast. In the northern portion of their range, they occur sparsely throughout broad temperate climate salt marshes, dominated by smooth cordgrass (*Spartina alterniflora*) and black needlerush (*Juncus roemerianus*). Mangrove recruits in northern reaches of their range die during periodic severe cold spells. In south Florida, mangroves dominate along tidal rivers and streams as well as in low energy coastal wetlands. There are three native mangrove species in south Florida: red (*Rhizophora mangle*), black (*Avicennia germinans*), and white (*Laguncularia racemosa*). Extensive mangrove forests occur along the southwest coast of Florida. The expanse of mangrove swamp in Everglades National Park measures approximately 1300 km^2 (500 mi^2) and constitutes a unique habitat of south Florida. Mangroves are prolific contributors to coastal fisheries because of their high productivity and nursery functions.





Ten Thousand Islands on the southwest Florida Gulf coast (left) is a vast expanse of mangrove islands and tidal creeks. Red mangroves located on an intertidal shoreline (right).

Coastal lagoons and bays

Pamela J. Fletcher, William L. Kruczynski, and Thomas E. Lodge

Many lagoons and bays are found throughout rural and urban areas of south Florida where freshwater mixes with saltwater. Biscayne Bay and Florida Bay are two large embayments that are characterized as shallow inner-shelf lagoons. Biscayne Bay provides a natural playground for a large urban population. Florida Bay consists of shallow interconnected basins, seagrass meadows, mud banks, and mangrove islands. Each of these features provides habitat for birds, reptiles, fish, plants, and a variety of benthic organisms. Bays along the southern portion of the Florida peninsula are mixing zones that link uplands and coastal nearshore areas to the Gulf of Mexico on the southwest coast and to the Atlantic Ocean on the southern and southeastern coasts. Bays and lagoons are important nursery habitats for many marine organisms and are susceptible to discharges of excess nutrients and other pollutants from land-based sources.

R. Molina

P.J. Fletcher - FSG

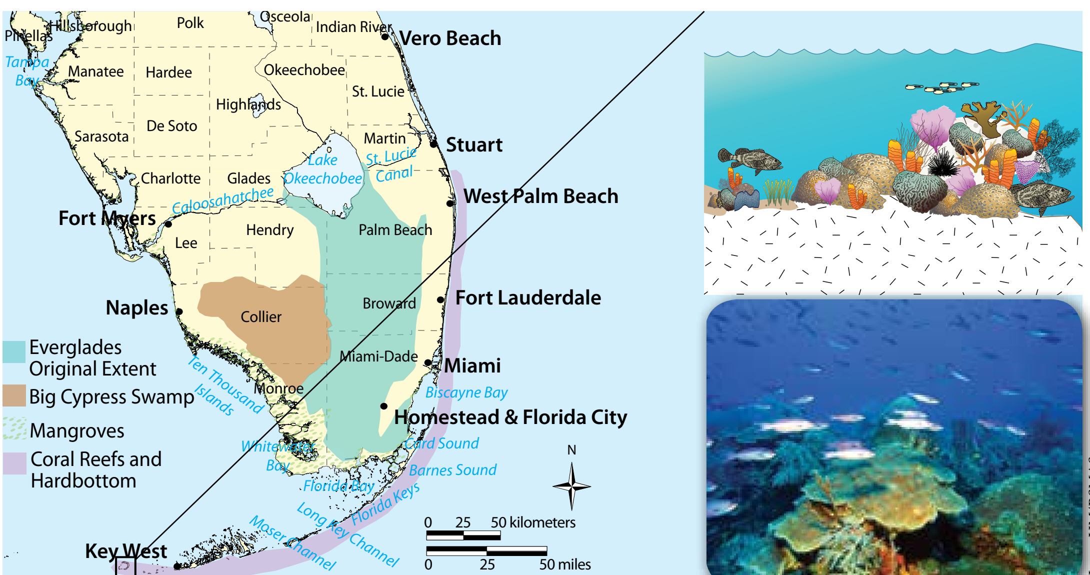
R. Molina

Bill Baggs Cape Florida State Park beach and lighthouse (left) attracts thousands of visitors each year to Biscayne Bay. View of Biscayne National Park from Elliott Key (right).

Coral reefs and hardbottom habitats

Pamela J. Fletcher, William L. Kruczynski

Coral reefs and hardbottom habitats are found throughout south Florida. Coral reefs are formed by reef-building corals that grow into vertical formations that provide habitat for a diverse flora and fauna that rivals tropical rainforests in biodiversity. Bank reefs occur at the continental margin in the Florida Keys and may consist of spur-and-groove formations. Patch reefs are small, roughly circular reefs that occur in nearshore waters. Coral reefs are important to the local economy and generate income by attracting tourists and supporting recreational and commercial fisheries. The Florida Keys Reef Tract is the only shallow water, tropical coral reef ecosystem in the continental United States. Hardbottoms are widely distributed and consist of limestone substrate that offers attachment sites for a variety of sea life, including sponges, soft corals, stony corals, bryozoans, and algae. Hardbottoms lack the vertical structure of reefs and are an important habitat for life stages of many organisms that make their way to coral reefs as adults.



Stony corals (left forefront) and soft corals (right) grow on the reefs and provide habitat for various life stages of fish and other marine animals.

The Florida Keys are a unique environmental setting

Billy D. Causey

At the tip of south Florida lie the Florida Keys, one of the most diverse assemblages of terrestrial and marine life in North America. This unique environmental setting was best described by Rachel Carson in *The Edge of the Sea* (1955) when she wrote:

"I doubt that anyone can travel the length of the Florida Keys without having communicated to his mind a sense of the uniqueness of this land of sky and water and scattered mangrove covered islands. The atmosphere of the Keys is strongly and peculiarly their own. ... This world of the Keys has no counterpart elsewhere in the United States, and indeed few coasts of the Earth are like it."

Biogeography is the study of patterns of species distribution. Biogeographically, south Florida and the Florida Keys are situated between warm, temperate waters and tropical waters of the Caribbean. This area is inhabited by fauna and flora of the West Indian, Carolinian, and Louisianian Biogeographic Provinces. South Florida is also at the crossroads of water masses that transport larvae from the Gulf of Mexico and the wider Caribbean basin. This environmental setting results in higher biodiversity in south Florida compared with other marine areas on the Atlantic and Gulf coasts.

South Florida is situated at the junction of the West Indian, Carolinian, and Louisianian Biogeographic Provinces, which results in a unique environmental setting and high biodiversity.

As visitors to the Florida Keys drive down U.S. Highway 1, the only highway connecting the Keys to the mainland, they may not realize that the marine environment is very different a short distance to the north in Florida Bay and the Gulf of Mexico compared with the south toward the coral reef tract and the Florida Straits. The marine environment in Florida Bay and the Gulf is influenced by the waters of the Southwest Florida Shelf. These waters are cooler in the winter and warmer in the summer than the more tropical waters of the Florida Current that bathe the coral reef tract to the south. There are many species of fish and invertebrates that live in Florida Bay or the Gulf that are not found on the coral reefs (e.g., speckled trout, *Cynoscion regalis*). Conversely, there are many species that live on Atlantic coral reefs that never make their way into the Bay waters (e.g., squirrelfish, *Holocentrus adscensionis*).

The Upper Keys are fossilized coral reefs that grew at the same time that the sand bars were forming in the Lower Keys, when the sea level was at least 6.1 meters (20 feet) above present. The current discontinuous chain of islands was formed when sea level fell and left the reefs (Upper Keys) and sand bars (Lower Keys) high and dry. The coral limestone substrate of the Upper Keys is called Key Largo Limestone. Newfound Harbor Keys, located seaward of Big Pine Key, are the western-most exposure of Key Largo Limestone. The highest elevation in the Keys is at Windley Key, 5.5 m (18 ft) above present sea level. Key Largo Limestone was once mined from Windley Key to build many of the old public buildings in Miami and the federal courthouse in Key West. The limestone quarry is now the Windley Key Fossil Reef Geological State Park, where visitors can walk on top of and inside the 125,000-year-old coral reef.

Strong ocean currents connect geographic regions

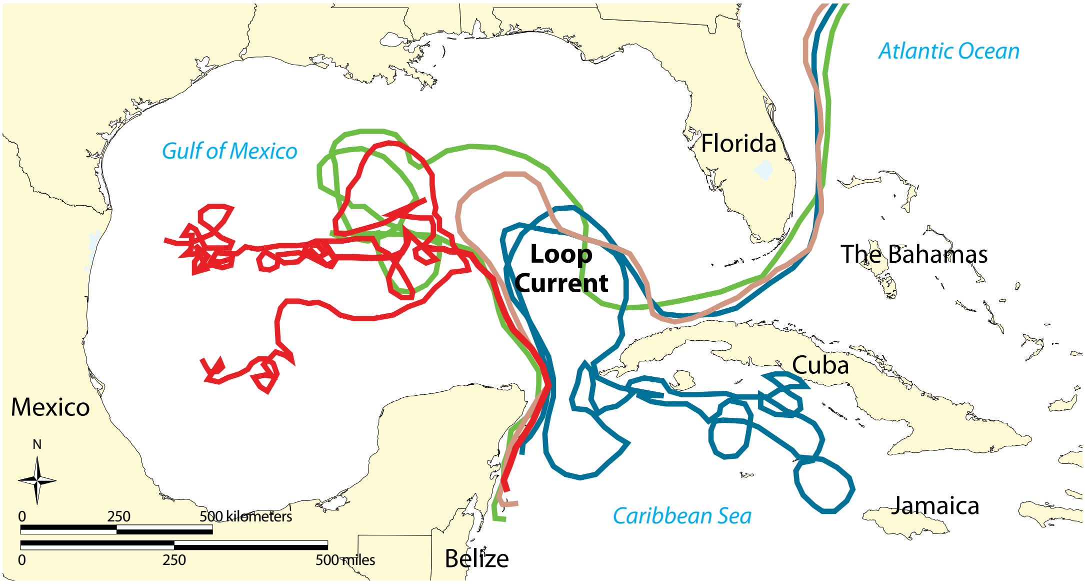
Brian D. Keller and Elizabeth Johns

Strong ocean currents connect south Florida with upstream waters of the western Caribbean Sea and the Gulf of Mexico. In particular, the Caribbean Current, emanating from the Caribbean Sea and flowing north past the Yucatán Peninsula, and the Loop Current in the Gulf of Mexico provide a rapid conduit for transport of materials from the Caribbean Sea, Mexico, and Belize into the coastal zones of northern Cuba, south Florida, and the Bahamas.

Planktonic larvae are dispersed by ocean currents. Thus, ocean currents between geographically separated reefs and marine habitats provide a means of biological connectivity between regional populations. This feature may have a direct influence on the ability of an ecosystem to recover from disturbances. For this reason, Marine Protected Areas should be strategically placed to maximize connectivity and protect biodiversity.

Dispersal of larvae can be simulated by computer models. At present, models are mainly useful in providing generalities and generating hypotheses. Studies of individual larval behavior, the ability of larvae to move up and down in the water column, and detailed life histories are required to produce more accurate simulations of population connectivity.

Currents also have the potential to carry pollutants, nutrients, diseases, and other stressors downstream to coral reef communities and other habitats. Cooperation between neighboring countries and an improved understanding of how external stressors degrade local marine resources are required to reduce negative impacts from upstream sources.



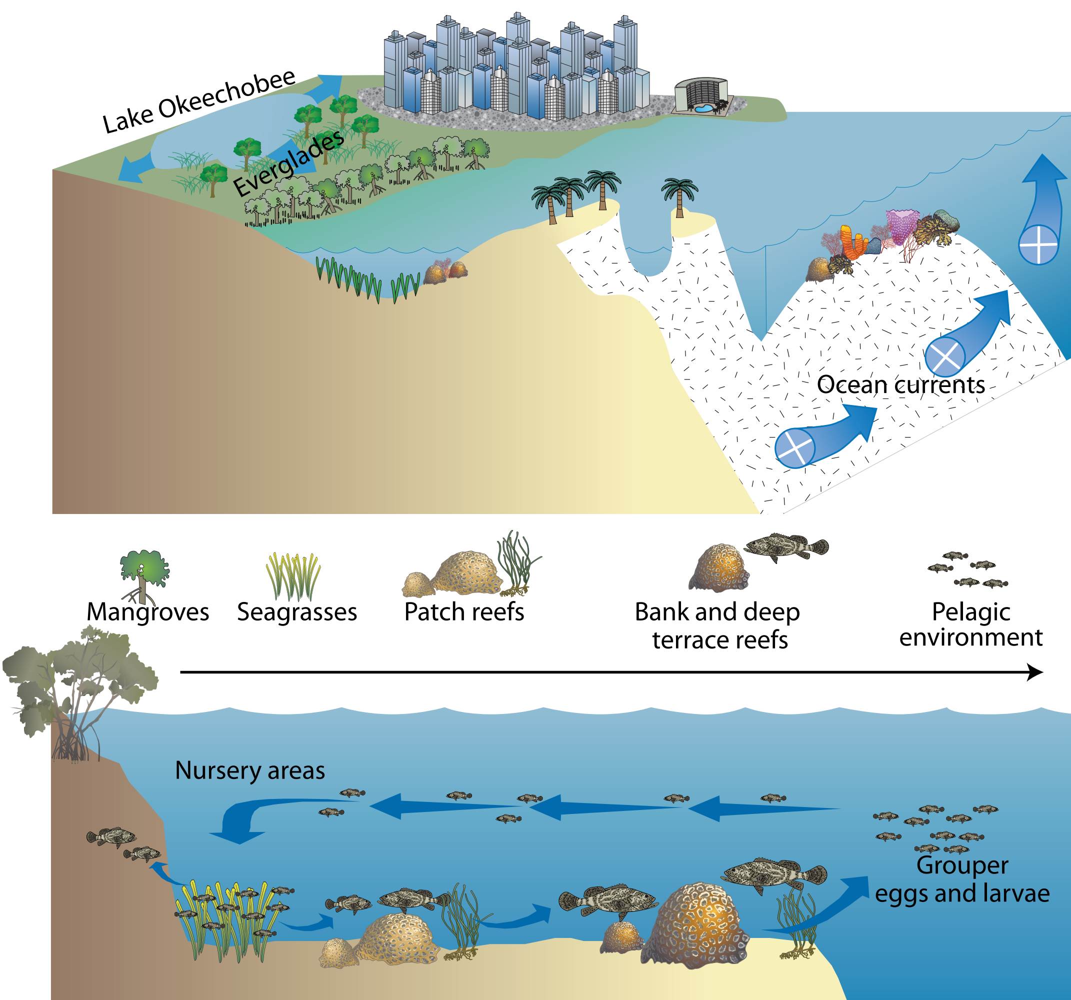
Trajectories of surface drifters deployed in March 2006 just east of the Yucatán Peninsula in Mexico show the complexity of regional currents. One drifter (red) became entrained in eddies in the western Gulf of Mexico and remained there. One (green) became entrained in eddies for a time and then joined the Loop Current and exited the Gulf of Mexico through the Florida Straits. One (orange) took a straightforward trip via the Loop Current, through the Florida Straits, and off to the North Atlantic. One (blue) meandered south of Cuba for several months before rejoining the Loop Current and rapidly exiting the area.

Marine and estuarine habitats in south Florida are physically and biologically connected

Jerald S. Ault

Unique bay-to-reef biological, topographic, and oceanographic conditions help to sustain the coral reef ecosystem of south Florida. Coastal benthic habitat types exhibit a distinct cross-shelf pattern from the shoreline to the deep reef, encompassing fringing mangrove forests, seagrass meadows, sponge and soft coral-covered hardbottoms, patch reefs, bank (i.e., barrier) reefs, and carbonate sediments. Many species of fish and invertebrates depend on this mosaic of environmental conditions and habitats found along the gradient from bays and lagoons to the bank coral reef.

South Florida is characterized by productive and highly diverse biological communities that include more than 500 species of fish and thousands of species of invertebrates, including corals, sponges, shrimps, crabs, and lobsters.



Schematic view of south Florida, including Miami and Biscayne Bay, showing physical connectivity of marine habitats and movement of life stages of grouper among habitat types.

Approximately 389 species of fish depend on a healthy coral reef ecosystem and support multi-billion dollar fisheries and tourism industries. The value of Florida recreational fisheries exceeds that of the state citrus industry and is 10 times more valuable than the state commercial fishing industry. Recognition of this fact contributed to the designation of Florida as the "fishing capital of the world" by the Florida State Legislature (1987).

South Florida is critically positioned at the nexus of complicated hydrodynamic influences. The seaward edge of the bank reef receives clear, low nutrient water from the Florida Current (that portion of the Gulf Stream current system in the Florida Straits) that provides conditions conducive to coral reef development. Periodically, the deep-reef margins receive pulses of nutrient-rich waters from locally intense upwelling events.

Gulf of Mexico waters mix with surface and groundwater from the Everglades and produce variable salinity regimes within an extensive network of coastal bays and lagoons with lush mangrove forests and seagrass meadows. The net movement of coastal waters along the Southwest Florida Shelf is southward through Florida Bay and toward the Atlantic Ocean and the fringing coral reefs.

Groupers and snappers are highly prized in commercial and recreational fisheries of south Florida. The bottom-dwelling stages of at least 50 species in the snapper-grouper complex use a broad array of habitats across the entire continental shelf. Most evidence suggests that strict estuarine dependence is a rare life history strategy among the species in the complex. However, many show some degree of habitat utilization and migration across the shelf as they mature. Habitat utilization patterns generally shift from coastal bays to offshore reef environments as individuals develop from juveniles to adults. Many species spawn at the seaward edge of bank reefs and sometimes form large spawning aggregations (e.g., goliath grouper). Pelagic eggs and developing larvae

NPS

Mangroves and seagrasses are important habitats in the life cycle of many marine species.

are transported from spawning sites to nursery habitats by a combination of tidal currents, seasonal wind-driven currents, and unique animal behaviors. Some of the most important nursery habitats are located in the coastal bays and near barrier islands and include mangrove and seagrass habitats.

Implications of habitat connectivity on fisheries management

Stressors to fisheries include overfishing, impacts of coastal development on habitats, and water quality degradation. The fact that many species depend on several coastal habitats throughout their life cycle complicates management strategies. It is important for management plans to consider protection for all habitat types used by the species throughout their life history to provide maximum protection to the fishery.

A major concern of fisheries management is the vast network of drainage canals in south Florida that were completed during the second half of the 20th century to facilitate rapid development of the coastal margin, conversion of wetlands for agriculture, and flood control. These canals have significantly altered the distribution of freshwater within the south Florida watershed and changed the historical quantity, quality, and timing of freshwater discharges to coastal bays. These alterations of natural drainage patterns have degraded marine habitats and resulted in dramatic environmental changes. A key management goal must be optimizing salinity gradients across the ecosystem, from mangrove shorelines to the coral reef, to ensure the ecological health of benthic habitats and the productive and diverse fisheries that they support.

Inputs from the Mississippi River, Southwest Florida Shelf, and other riverine sources can affect water quality, produce algal blooms, and reduce habitat suitability and fishery resources in south Florida. Thus, the geographic scale of future fisheries management actions may need further refinement from those historically used.

The need to unify coastal land management with fishery management was reinforced by the Essential Fish Habitat (EFH) provisions in the reauthorization of the Magnuson-Stevens Act. EFHs are "those waters and substrate necessary to fish for spawning, breeding, feeding, or growth to maturity." EFH guidelines recognized Habitat Areas of Particular Concern (HAPC) by at least four criteria:

1. Importance of ecological functions;
2. Sensitivity to degradation;
3. Probability and extent of effect from development; and
4. Rarity.

The Act provides that if a species is overfished, all habitats it uses are considered essential. Sites that consistently support spawning aggregations for multiple species require management as EFH-HAPC and potentially should be set aside as no-take protected areas.

Nursery habitats are particularly vulnerable to impacts from coastal development. Establishment of Marine Protected Areas (MPAs) can only be effective if connectivity among habitats is recognized, and the design of MPAs is coordinated among all agencies responsible for regulating development, water quality, fisheries, and habitat protection.

The Comprehensive Everglades Restoration Plan projects a 30-year implementation program to restore the Everglades ecosystem and adjacent estuaries. An important aspect of the restoration plan must be to optimize the expected changes to the entire coastal ecosystem.

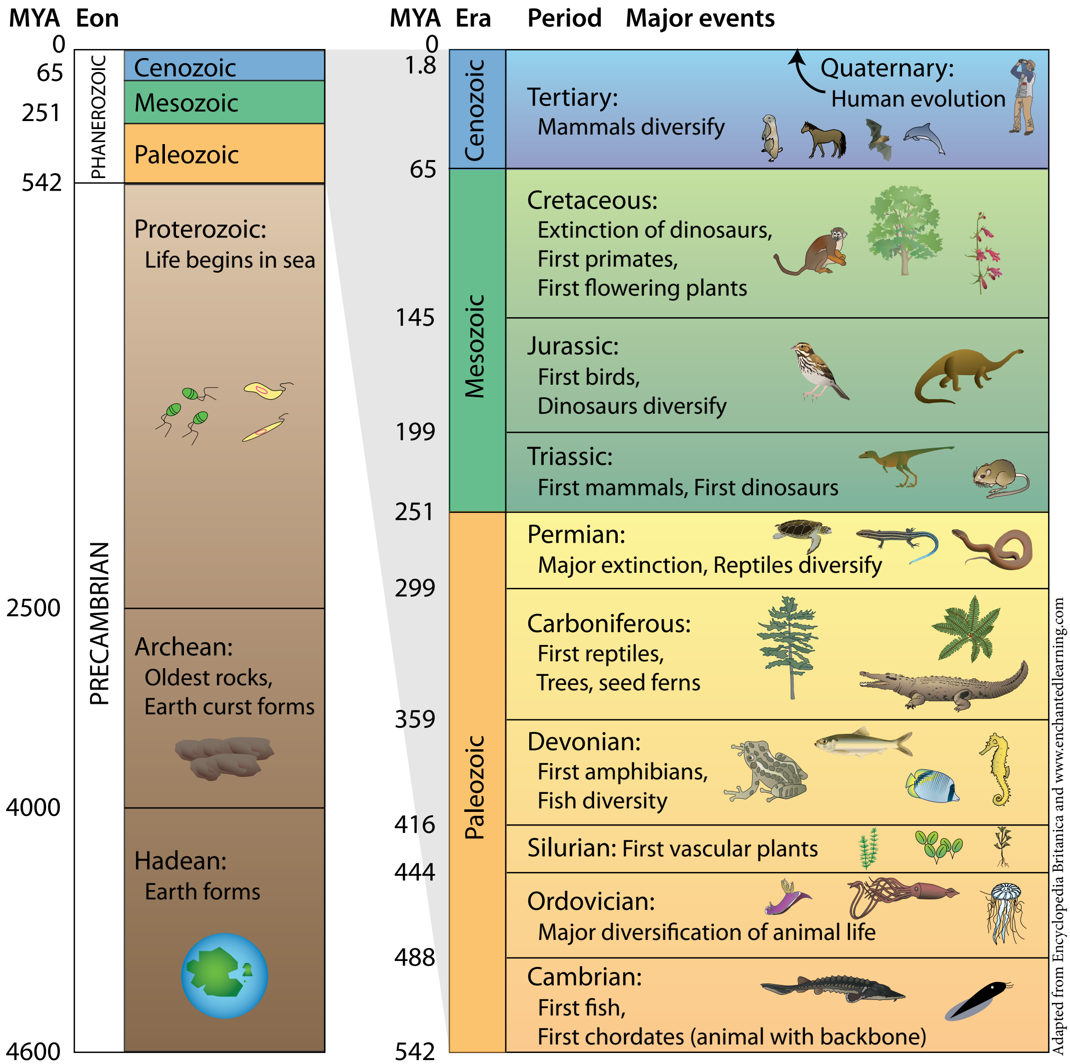
FDOT

FDOT

Example of coastal habitat loss in south Florida. Extensive coastal habitats, including mangrove forests that were present near the mouth of the Miami River in 1956 (left), are replaced today with extensive development (right).

Geological time with major evolutionary events in the fossil record

William L. Kruczynski and Pamela J. Fletcher



The geological time scale is a method of relating the timing and relationship between events that have occurred during the history of the Earth. The Earth is more than 4.5 billion years old, and an appreciation of the expanse of geological time is difficult to visualize. This chart shows the sequence of major evolutionary events that appear in the geologic record. Geologists and earth scientists have used the relationship between layers and types of rocks, presence of plant and animal fossils, and radioactive dating to assemble a sequence of historical events that have occurred over geologic time.

Geologic time is divided into four large segments called Eons: Hadean, Archean, Proterozoic, and Phanerozoic. The Phanerozoic Eon is divided into Eras: Paleozoic, Mesozoic, and Cenozoic. The divisions among Eras reflect major changes in the fossil record, including the extinction and appearance of new life forms. Eras are divided into Periods, a unit of geologic time in which a single type of rock system is formed. Some Periods are divided into Epochs that are not shown on this chart, but a discussion of Epochs appears on subsequent pages in this chapter that summarize the creation of the Florida peninsula, the geology of south Florida and the Florida Keys, and the appearance and disappearance of shorelines and coral reefs.

Dates from the International Commission on Stratigraphy, 2010. MYA = Million years ago.

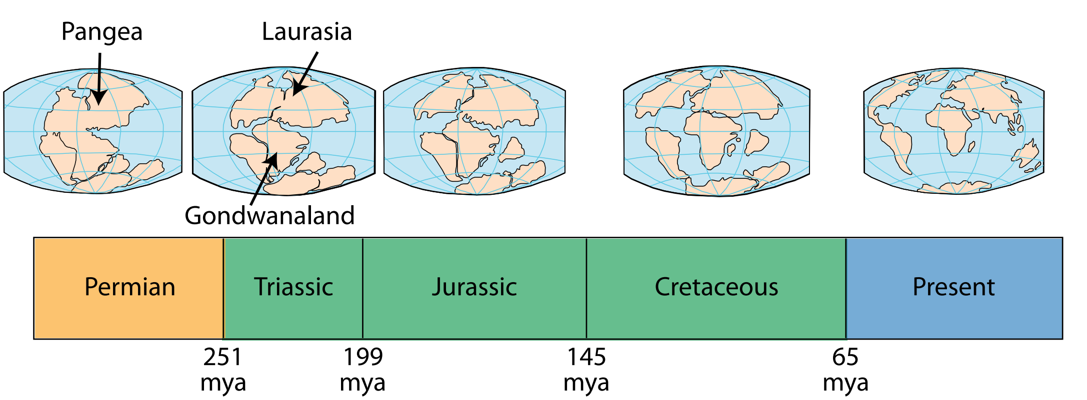
Florida has changed over millions of years

Guy H. Means

The Earth is more than 4.5 billion years old. During this unimaginable expanse of time, our planet has undergone drastic changes. For the earliest part of the history of the Earth, the planet was a molten inferno. As the planet slowly cooled, rocks and minerals began to form, and continents and ocean basins took shape. The continents today look nothing like they did hundreds of millions of years ago. In fact, the continents move around through a process called "plate tectonics." Continental crust, the thin outer skin of our planet, sits on top of hot rock material that behaves like cold syrup and is called the mantle. As the plates shift, they can collide, causing mountain ranges and deep ocean trenches to form. They can also slide past one another along long faults, like the San Andreas fault in California, and they can spread apart as seen along mid-ocean ridges. Plate tectonics describes the processes involved with plate movements and allows geologists to understand the changes in the Earth's landforms.

The geological history of south Florida can be traced back to the Paleozoic Era, 542 – 251 million years ago (mya), based on rock core samples retrieved from thousands of meters below the surface. These rocks, referred to as "basement rocks," consist of igneous and metamorphic rocks overlain by sandstones and shales. The sequences of rock layers record the events that were taking place as the Laurentian and Gondwanan landmasses were converging to create the supercontinent of Pangea. As these and other smaller landmasses converged, they created the foundation for the accumulation of vast thicknesses of carbonate (limestone) that would eventually become the Florida Platform.

During the early Mesozoic Era (251 – 65 mya) the supercontinent of Pangea began to rift and break apart. Florida, during this time, was located between what would later become the continents of Africa, South America, and North America. In fact, as North America separated from Africa, a small portion of the African plate remained "stuck" to North America and that provided some of the foundation upon which Florida now rests. Geologists can tell this by looking at the chemistry and fossil assemblage of Florida basement rocks. During the later part of the Mesozoic Era, the Florida landmass was beneath a warm, shallow ocean. As

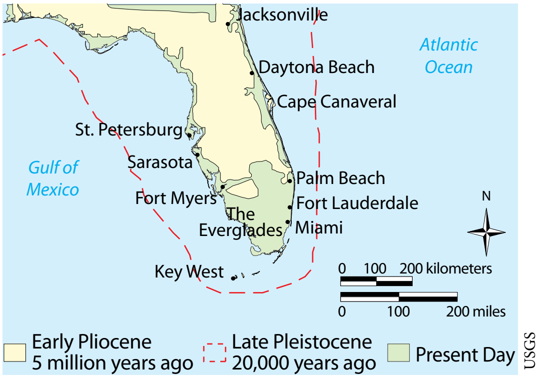


During the Permian Period (299 – 251 million years ago [mya]), the continental plates on Earth joined together to form the supercontinent Pangea. During the Triassic Period (251 – 199 mya), the supercontinent broke apart. As this happened, a small portion of Africa remained attached to North America, which created the foundation that Florida now rests upon.

marine organisms died and sank to the ocean floor they began to accumulate in great thickness. This sediment would later consolidate and become limestone. The end of the Mesozoic Era was brought about by a great cataclysm, when a large meteor impacted the Earth in what is now the Yucatán Peninsula. It is believed that this event caused mass extinction of many species, including the dinosaurs.

During the Cenozoic Era (65 mya – present), Florida slowly took its current shape. Warm, tropical oceans covered the state until the late Oligocene Epoch (34 – 23 mya). Large, voracious whales roamed the shallow seas hunting other marine vertebrates. Small patch reefs formed in the warm, clear, shallow waters of Florida during this time. The skeletons of billions of small creatures, called "foraminifera" accumulated on the seafloor. These skeletons would later become cemented together to form limestone, which underlies the entire state of Florida. Also during this time period, a marine current similar to the Gulf Stream swept across northern Florida and scoured the seafloor. This current deflected sediments, such as silicate sands, that were being eroded and transported from the north, and this is the reason why limestones from this time period in Florida are so pure (up to 99% calcium carbonate). At the end of the Oligocene Epoch, sea levels dropped, and Florida emerged from the sea. The first fossils of terrestrial vertebrates in Florida come from this time period and include animals like bats, horses, and carnivores. From this time period on, at least some portion of Florida would remain above sea level. Throughout the end of the Oligocene and into the Miocene Epoch, sea levels fluctuated, and clays and sands became common deposits.

The Miocene Epoch (23 – 5.3 mya) was a time of unique conditions across Florida. Large deposits of phosphorite accumulated as cool, nutrient-laden ocean water bathed southern Florida. These deposits are mined today and account for a significant portion of the phosphate produced in the United States. Unique creatures also existed in Florida at this time. Large sharks patrolled the nearshore marine environments preying on whales. Horses, saber-toothed cats, and elephants roamed the land. Many of these creatures left behind their bones in Miocene deposits. A prized fossil from this time period is the tooth from the giant extinct shark (*Carcharodon megalodon*). These teeth can exceed 180 centimeters (7 inches) in length and belonged to an animal that may have been 20 meters (67 feet) long!



Land area of Florida during the Early Pliocene, Late Pleistocene (red dotted line), and present-day Florida.

The Pliocene Epoch (5.3 – 2.6 mya) was an important time for land animals in Florida. North America became connected to South America, allowing animals to travel freely between both continents. North America became the home to animals like sloths, giant armadillos, and llamas that migrated north over the newly formed land connection. Ocean currents were also interrupted and the Gulf of Mexico became isolated from the influence of the Pacific Ocean. The exchange of flora and fauna from South America is known as the Great American Interchange. Sea levels were fluctuating, and marine deposits (limestone and shell beds) were accumulating in south Florida. Those shell beds contain some of the most diverse molluscan faunas in the world.

The Pleistocene Epoch (2.6 mya – 11,000 years ago), also known as the Ice Age, was a time of extreme climate and sea level changes. Sea levels were about 123 m (400 ft) lower and as much as 30 m (100 ft) higher than today. As the giant continental glaciers advanced and retreated, sea levels responded. During warm, interglacial periods, sea levels were sufficiently high to allow marine limestones to accumulate. During glacial periods, sea levels were much lower, and erosion and dissolution of limestone occurred. Giant Ice Age mammals roamed Florida at this time and included some of the largest land mammals to have ever existed. Some of these animals include mammoths, mastodons, giant lions, Dire wolves, saber-tooth cats, giant sloths, and giant beavers. At the end of the Pleistocene, another animal arrived in Florida: humans. This also coincided with the demise of the giant Ice Age mammals. Many large mammals went extinct at the end of the Pleistocene either as the result of climate change, human hunting, or a combination of both.

Sea level reached its current elevation during the Holocene Epoch (11,000 years ago – present). Human populations expanded and shaped the landscape to suit their needs. The Everglades of south Florida formed, and thick layers of peat were deposited. The Florida Keys became islands, and new coral reefs began to grow. Our modern climate developed, and Florida took the shape we are all used to seeing: a long peninsula.

MYA	Era	Period	Epoch	Major Events
0	Cenozoic	Quaternary	Holocene	Climate change and sea-level rise. Florida Keys become islands. Current bank reefs form. Everglades form. Sea level at present level.
0.011			Pleistocene	Humans arrive in Florida. Mastodons roam. Ice Age causes extreme changes in climate and sea level. Sea level drops about 123 meters (400 feet) below present level. During warm periods, sea level was about 30 m (100 ft) above present level and allowed exchange of Atlantic and Gulf of Mexico faunas. Coral reefs that would eventually become the Florida Keys grow and accumulate. Humans evolve.
2.6		Tertiary	Pliocene	North and South America joined. Giant sloths and llamas found in Florida. Gulf of Mexico isolated from Pacific Ocean.
5.3			Miocene	Phosphate deposits accumulate. Giant sharks (*Megalodon*) roam the seas. Horses, saber-toothed cats, and elephants roam landmass. Clays and sands deposited from north.
23			Oligocene	Thick deposits of limestone. Sea level drops, Florida landmass emerges. First land animal fossils.
33.9			Eocene	Warm period, oceans teem with fish. Palm trees range as far north as Alaska. Foraminifera accumulate on seafloor.
55.8			Palocene	Evaporite minerals accumulate in shallow, restricted marine water areas.
65	Mesozoic	Cretaceous		Extinction of dinosaurs. Marine sediments continue to accumulate.
145		Jurassic		Marine sediments form thick limestone deposits.
199		Triassic		Plate tectonics result in separation of Florida landmass from Africa.
251	Paleozoic			Basement rocks accumulate.
542				

Adapted from Lane (1994)

A brief geological history of Florida.

Geology of the Florida Keys

Eugene A. Shinn

The Florida Keys are approximately 125,000 years old. It is a common belief that the Keys landmass of today is just old exposed corals, but it is more complex than that. The Keys can be divided geologically into the Upper Keys, from Bahia Honda Key northward, and the Lower Keys, from Big Pine Key to Key West. The Lower Keys are cemented fossil tidal bars of ancient sands. These sand bars consisted of small concentric grains of calcium carbonate called ooids that precipitated from warm high-energy waters. When ooids are cemented together to form limestone, the resulting "rock" is called oolite. This formation is also found under the city of Miami. Similar ooid sand bars are currently forming in the Bahamas, but for unknown reasons ooids ceased precipitating in huge quantities in the Florida Keys after the fossil bars formed 125,000 years ago. The north-south shape of the Lower Keys from No Name Key to Key West is due to strong tidal currents that once raced between the Gulf of Mexico and the Atlantic Ocean when sea level was higher than present, and the currents eroded channels through the tidal bars.

The Upper Keys are fossil coral reefs. These reefs grew at the same time sand bars were forming in the Lower Keys when the sea level was at least 6 meters (20 feet) above present. The current discontinuous chain of islands was formed when sea level fell, leaving the reefs (Upper Keys) and sand bars (Lower Keys) high and dry. This coral limestone of the Upper Keys is called Key Largo Limestone. Newfound Harbor Keys are the westernmost exposure of the Key Largo reef. The highest elevation in the Keys is at Windley Key, 5.5 m (18 ft) above present sea level.

The fossil reef that forms the Upper Keys is much more permeable than the oolitic limestone in the Lower Keys. Big Pine Key is a large oolite island and has a 6 m (20

NASA

Satellite image showing the current shape of the Lower Florida Keys landmass.

Geographic Setting and Impacts to the Environment

Years ago	Period	Epoch	Major Events
50	Quaternary	Holocene	1950 -1970 Keys development increases and canals are built.
100			1912 Flagler's Railroad disrupts Gulf-Atlantic water exchanges.
200			1821 Indian Key becomes U.S. property. 1763 Native Indians no longer present in the Keys.
300			1733 First map of the Florida Keys.
500			1513 Ponce de Leon "discovers" the Keys.
2000			Oldest Indian shell midden dated.
11,000			
12,000		Pleistocene	Sea level begins rising rapidly.
13,000			Paleo Indians arrive.
17,000			Florida Keys and Florida Bay are forested; Hawk Channel is a swamp.
18,000			Last glacial period, warming begins and glaciers melt. Sea level 123 meters (400 feet) lower than present-day.
120,000			Coral reefs that form the Florida Keys landmass are dry. Sea level 6 m (20 ft) higher than present-day. Quaternary Units (Q1 – Q5) form during periods of low water. Reefs flourish during interglacial periods.
1,800,000			During glacial periods, corals grow at the edge of the continental shelf. Ice Age begins, and there are four periods of glaciation.

Adapted from Lane (1994) and Viele (1996)

A brief history of the Florida Keys during the Quaternary Period (time record is not to scale).

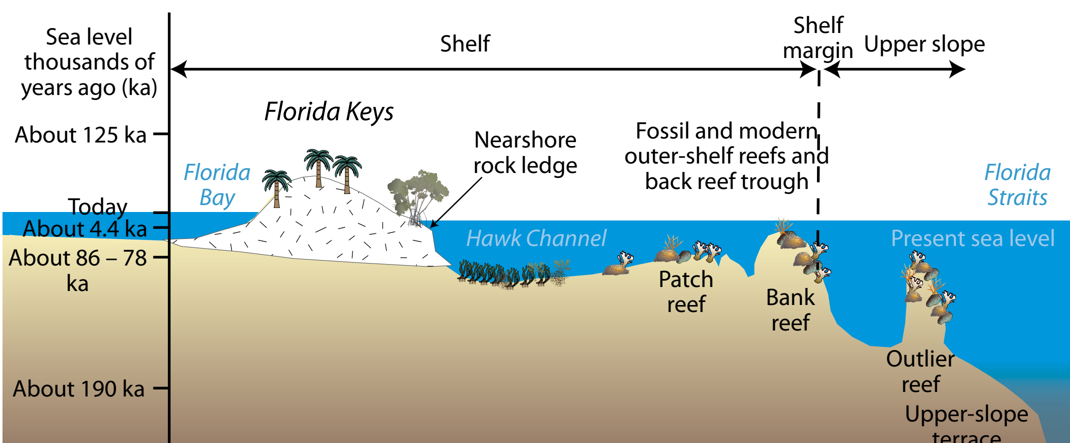
ft) thick freshwater lens just below the surface. The lens floats on the underlying salty groundwater and is not greatly affected by the tides because of the low permeability of the oolite. The south Florida slash pines (*Pinus elliotii* var. *densa*) for which the island is named depend on this freshwater lens to survive. Tides flush through the Key Largo Limestone more rapidly and remove any freshwater that accumulates beneath the surface. This is one reason that there are no pine trees in the Upper Keys.

The Florida Keys were formed in the Pleistocene Epoch, a time period from 1.8 million years before present until 11,000 years before present. It was a time that includes the most recent period of repeated glaciations in the world. During glacial times, sea level fell because water was locked up in the polar ice caps; during interglacial times, sea level rose as the ice caps melted. Each time the sea rose, rows of coral reefs formed on the shelf seaward of the present Florida Keys. Each time the sea fell, the reefs were left exposed, and rainwater dissolved and cemented them into hard limestone. The exposed reefs were also coated with a distinctive dense crust called Q1– Q5 Units (Q = Quaternary). That brown-colored crust can be seen in areas of exposed limestone. The last big drop in sea level was about 28,000 years ago, when the sea level fell more than 123 m (400 ft). About 10,000 years ago, the sea began rising fast and flooded the old offshore reef areas in about 3000 – 4000 years. Those older reef areas became the foundation of the present reef growth. The modern barrier reefs that make up the Florida Keys Reef Tract were formed in the Holocene Epoch, a time period from 11,000 years ago to the present, and are essentially a recolonized growth of corals, algaes, and other benthic organisms on old dead reef structures.

What lies below the Pleistocene rocks is, of course, much, much, older. The Pleistocene marine sequences accumulated on top of more than 4.6 kilometers (2.8 miles) of pre-existing limestone. About 3.4 km (2.1 mi) below the Pleistocene rocks are limestones that belong to the Cretaceous Period (the time of the dinosaurs) that ended about 65 million years before present. The limestone was dated from rock fragments recovered from the 14 oil wells drilled in the Keys since the 1940s (the last in 1961). Underneath the Cretaceous rocks are those belonging to the Jurassic Period.

A.S. 'Buddy' Wylie, Jr. - COGE

Key Largo Limestone consists of fossilized coral reef as seen in canals in the Florida Keys.



Pleistocene geomorphic features	*Shallow inland lagoons or embayments (Florida and Biscayne Bays)*	*Key Largo Limestone and Miami Limestone*	*Shallow near-shore rock ledge*	*Broad trough-like depression lined with soft sediments*	*Ridge of 86 – 78 ka corals underlying Holocene accumulations and forming shelf-margin edge*	*Upper-slope terrace (about 190 ka) 1) Seismic profiles reveal outlier reefs on upper slope terrace 2) Facies and aerial photographs indicate high-relief outlier reefs and deep troughs on terrace off the Lower Keys 3) Youngest Pleistocene corals on the outlier reefs and shelf-margin reef are the same age (86 – 78 ka)*
Depth (relative to present sea level)	*-2 to -3 m*	*0 to +5.5 m above sea level*	*0 to -4 m*	*-8 to -16 m average*	*-6 to -15 m*	*-30 to -40 m*

Adapted from Lidz (2005)

Timeline of recent geologic events in the Florida Keys and reef tract.

Geographic Setting and Impacts to the Environment

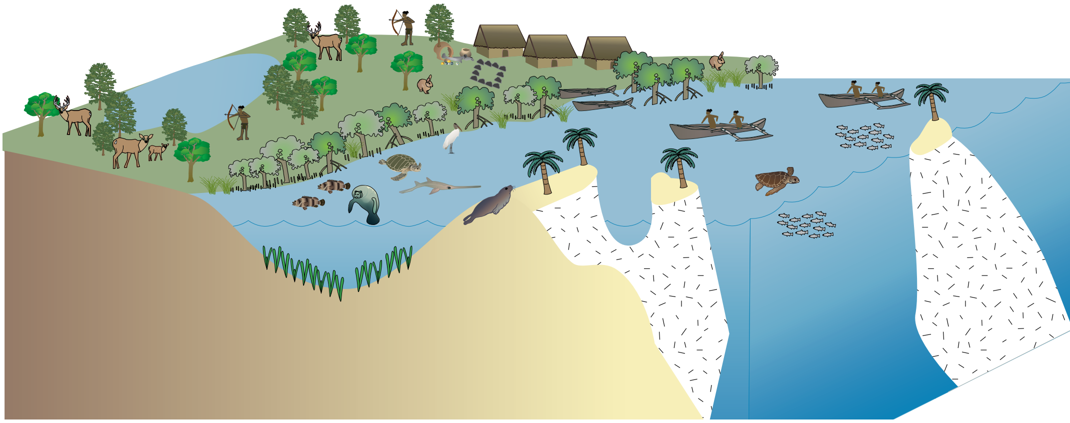
Humans have significantly impacted south Florida and the Florida Keys

William L. Kruczynski and Pamela J. Fletcher

BIRDS			
Wood stork	*Mycteria americana*	■	Endangered
MAMMALS			
Key deer	*Odocoileus virginianus clavium*	■	Endangered
Florida panther	*Puma concolor coryi*	■	Endangered
Silver rice rat	*Oryzomys palustris natator*	■	Endangered
Florida manatee	*Trichechus manatus*	■	Endangered
Caribbean monk seal	*Monachus tropicalis*	■	Extinct
Key Largo woodrat	*Neotoma floridana smalli*	■	Endangered
Lower Keys marsh rabbit	*Sylvilagus palustris hefneri*	■	Endangered
Key Largo cotton mouse	*Peromyscus gossypinus*	■	Endangered
FISH			
Largetooth sawfish	*Pristis perotteti*	■	Critically Endangered
Smalltooth sawfish	*Pristis pectinata*	■	Critically Endangered
Sandbar shark	*Carcharhinus plumbeus*	■	Threatened
Goliath grouper	*Epinephelus itajara*	■	Critically Endangered
Scalloped hammerhead	*Sphyrna lewini*	■	Endangered
REPTILES			
American crocodile	*Crocodylus acutus*	■	Threatened
Green turtle	*Chelonia mydas*	■	Endangered
Kemp's ridley turtle	*Lepidochelys kempii*	■	Endangered
Loggerhead turtle	*Caretta caretta*	■	Threatened
Leatherback turtle	*Dermochelys coriacea*	■	Endangered
CORALS			
Elkhorn coral	*Acorpora palmata*	■	Threatened
Staghorn coral	*Acorpora cervicornis*	■	Threatened

■■■ U.S. Endangered Species Act list ■ International Union for Conservation of Nature (IUCN) list

Before the arrival of humans, south Florida waters were a much different place than they are today. The region teemed with life, including large herbivores and predators. The land supported a diverse assemblage of wildlife, including deer, bear, panther, and their prey. The history of south Florida is a story of human attempts to conquer the land, resulting in habitat destruction, habitat fragmentation, overfishing, and pollution. Today, humankind is trying to manage a very different ecosystem than the one that existed in the past. There are few places on Earth that have as many endangered, threatened, and overfished species as south Florida.



By 100 A.D. the Native American population increased to about 1000 inhabitants. They were hunter-gatherers and obtained much of their food from the sea. Because of their small numbers, sustainable harvesting practices, and general respect for the Earth, they had negligible impacts on the environment.

1000 BC – 700 AD
Dates given to many Upper Keys Native American archaeological sites.

1700s – 1800s
White man's guns, disease, rum, and raids by northern Indian tribes wiped out Keys natives. Keys are deserted.

1513 – Ponce de Leon expedition "discovered" the Florida Keys while searching for the Fountain of Youth.

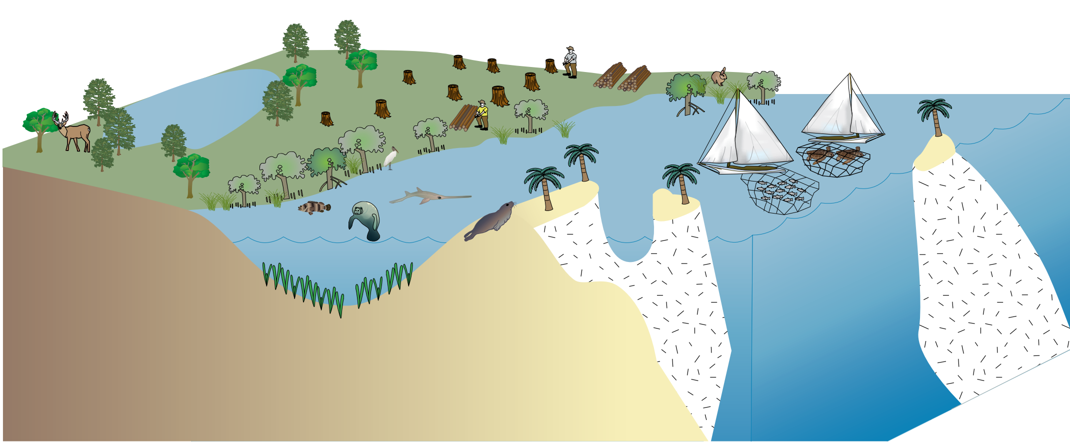
1821 – Florida became a U.S. territory.

1825 – Cape Florida lighthouse built on Key Biscayne to warn ships of dangerous coral reefs. The lighthouse was burned by the Seminoles in 1836.

1836 – 1842 – Second Seminole War occurred over demand by U.S. government that Indians relocate to western reservations. Indian war parties raided Key Largo and Indian Key. Population of settlers in Miami area was decimated.

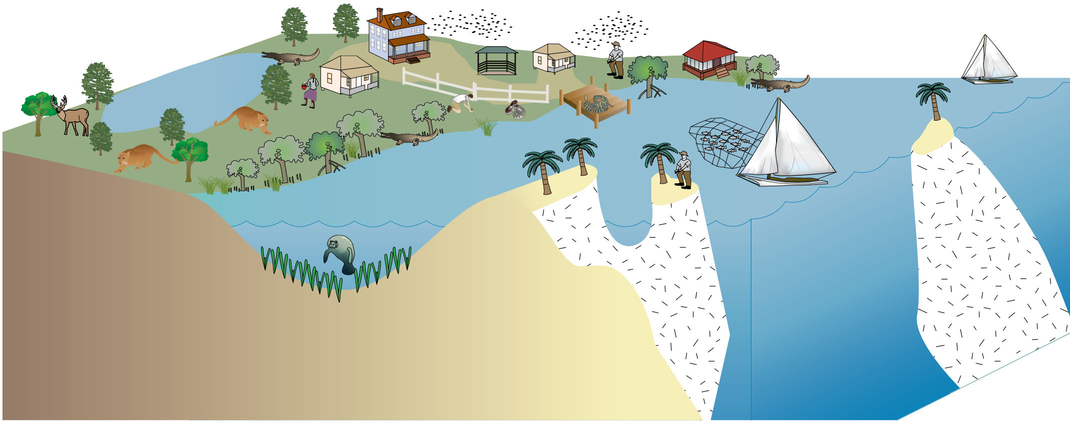
1845 – Florida became a U.S. state.

1850 – First census: 32 settlers lived among Summerland, Sugarloaf, and Boca Chica Keys; 40 settlers lived on Key Vaca.



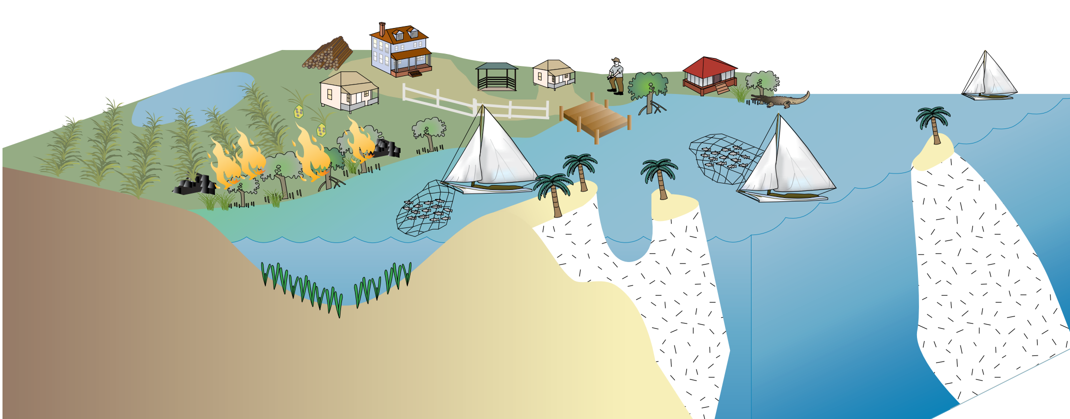
Cubans and Bahamians visited the Keys to fish, catch turtles, harvest hardwood timber, and salvage shipwrecks. Most valuable timber was probably gone by 1760. After the War of 1812, New England fishermen came to the Keys in the winter to fish. They were among the first settlers of Key West.

Adapted from Viele (1996) and The Florida Keys Environmental Story (1997)



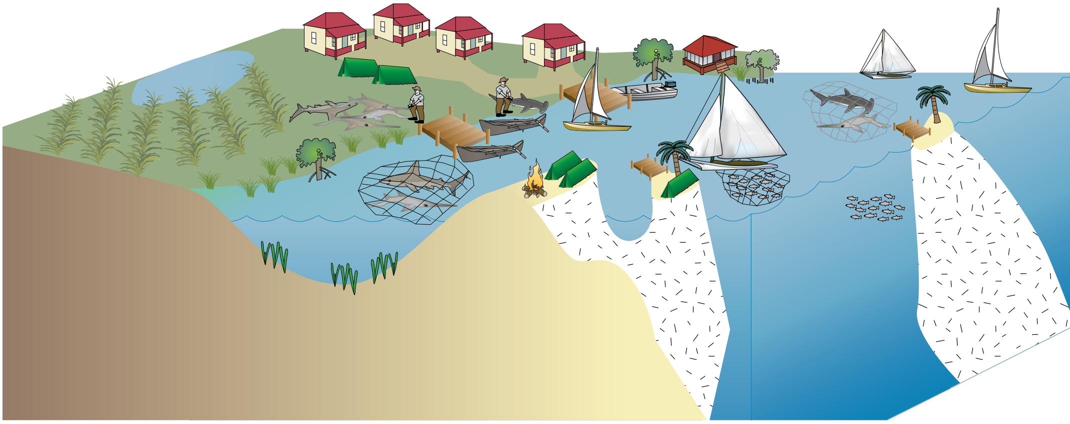
Heat, rattlesnakes, mosquitoes, no-see-ums, alligators, panthers, and scarcity of freshwater made life difficult in the Keys. Before the first highway, all inter-Keys commincation and communication with the mainland was by boat.

- **1870** — Population outside Key West was about 300 inhabitants.
- **1890s** — Key West was the largest city in Florida (18,000 people) with an economy based on the cigars, sponges, and shipwreck salvages.
- **1905 – 1912** — Henry Flagler financed the construction of the Overseas Railroad ($50 million in 1905 dollars). The Railroad spanned 171 km (106 mi), connected 31 islands, and included 27 km (17 mi) of bridges and 32 km (20 mi) of filled causeways. Turbidity negatively impacted seagrasses and corals and degraded sponging and fishing grounds.
- **1906** — Canals were dug to drain water from the Everglades for agriculture and to create land for development.
- **1917 – 1928** — First Overseas Highway was constructed, making it possible to ferry or drive by automobile from Miami to Key West. Ease of access brought many recreational fishermen to the Keys.
- **1918** — Seaplane base was established in Key West for training and anti-submarine patrol. After WWII ended, some military personnel stayed in the Keys.

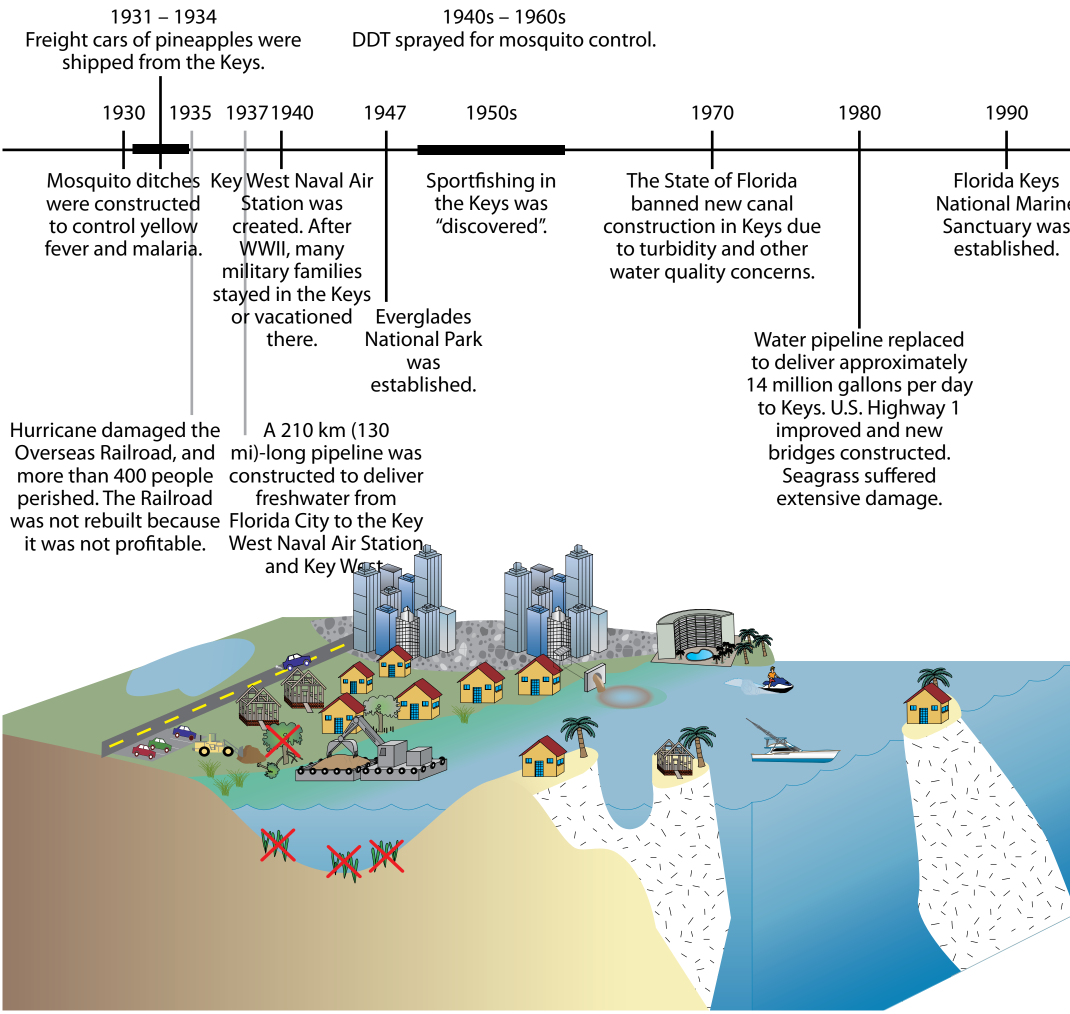


Adapted from Viele (1996) and The Florida Keys Environmental Story (1997)

Many early settlers were farmers, and a main crop was pineapples in the Upper Keys and fruits and vegetables in the Lower Keys. Many made a living fishing, gathering sponges, or making charcoal for Key West stoves. Rampant habitat loss and fragmentation to "conquer" the Keys begins. Hardwood hammocks were cleared for farming.



By 1930, fishing camps were popular in the Keys. Big Pine Shark Camp commercially harvested up to 100 large sharks and sawfish per day. The long-lived and slow-reproducing fish were virtually eliminated from the Keys and have not recovered to this day.



The period 1948 – 1970 marks a building boom to create waterfront housing by dredging and filling mangroves and seagrasses. Approximately one half of the mangroves in the Keys were destroyed. Turbidity was chronic and smothered seagrasses and corals. Sewage and stormwater controls were primitive or nonexistent.

Adapted from Viele (1996) and The Florida Keys Environmental Story (1997)

Paleoecologists interpret south Florida's past

C. Lynn Wingard

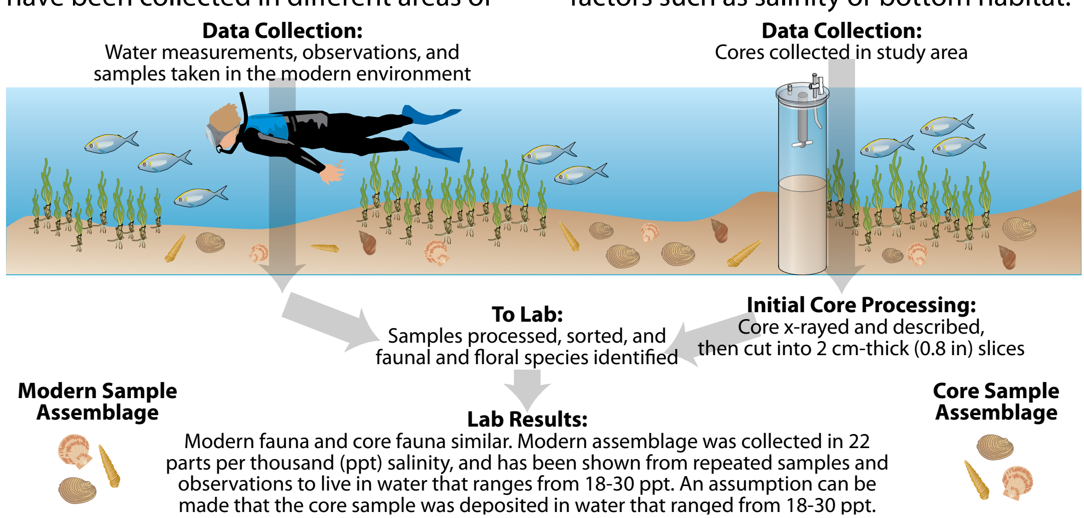
One way to understand what an environment looked like in the past is to examine the remains of plants and animals in samples collected throughout an area being studied. This is what paleoecologists do: they study the remains of plants and animals that lived in the past (paleontology) and they interpret the interaction of those plants and animals with their environment (ecology).

Paleoecologists need two types of information to interpret the history of an ecosystem: 1) the remains of plants and animals that lived in the past collected from sediment cores and 2) the ecological requirements of the living organisms found within the ecosystem.

Cores are used to collect layers of sediment with plant and animal remains while maintaining their vertical arrangement relative to each other. Each layer tells the "story" of what the ecosystem was like at a particular point in time. The most recent part of the story is preserved in the upper layers of the core; the lower layers of core material show older periods in time. By examining the changes from layer to layer, scientists can develop a picture of the changes that occurred over time. In south Florida, cores have been collected in different areas of the estuaries to compare what happened across the region at the same time.

Once a core is collected, it is X-rayed, photographed, described, and then sliced into approximately 2 centimeters (0.8 inches)-thick samples. The plant and animal remains are counted and identified, and the distribution of key organisms in the core is recorded. Changes in the number and types of plants and animals in the core reflect changes to the environment.

Paleoecologists work on the principle that "the present is the key to the past." In south Florida estuaries, factors that control the distribution of living species of plants and animals are salinity, water temperature, water depth, and type of bottom environment. Understanding the ecological requirements of the plants and animals alive today allows scientists to interpret the environmental conditions represented in the layers of the cores. Species found in the core samples that currently live in south Florida are assumed to have had the same set of environmental conditions observed today. Compiling the changes in the core assemblages over time illustrates the environmental changes over time of factors such as salinity or bottom habitat.



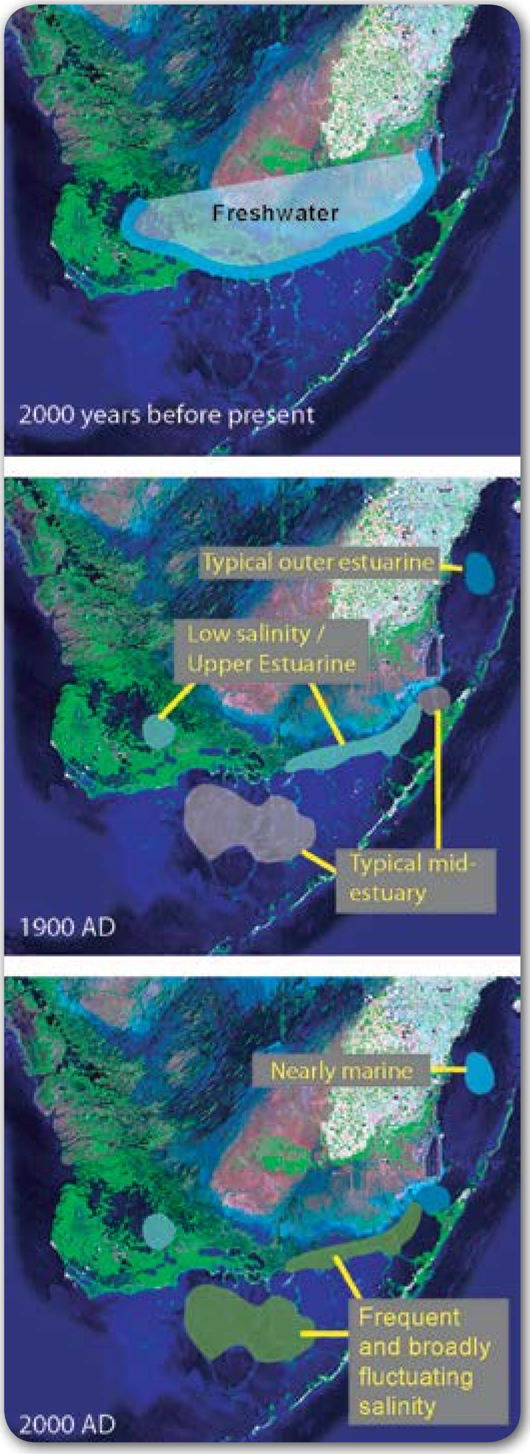
From Wingard (2004)

South Florida estuaries have changed over time

C. Lynn Wingard and Frank E. Marshall

South Florida estuaries may have been quite different in the past compared to present-day conditions. Analysis of sediment cores shows that over the past 2000 years, the salinity in south Florida estuaries has been gradually increasing due to rising relative sea level. During the 20th century, the rate of change in salinity increased significantly. Most scientists attribute this change in salinity to a combination of the increase in the rate of sea-level rise and a decrease in the supply of freshwater to the estuaries because of drainage modifications for agricultural and urban flood protection and for development.

Changes in salinity are critical to an ecosystem because salinity patterns within an estuary are one of the primary controls over distribution and diversity of living organisms. Approximately 2000 years ago, freshwater environments extended into nearshore areas that are currently estuarine along the transition zone of Florida Bay, Whitewater Bay, and the Shark River. By the beginning of the 20th century, evidence from sediment cores shows a change to relatively typical faunal patterns for a zoned estuarine ecosystem. In a zoned ecosystem, more marine salinities occur in open areas of the bays, and lower salinities occur in the upstream transition zones (e.g., between the Everglades wetlands and the estuaries).



Salinities in Florida Bay and Biscayne Bay based on the fauna from core samples. Top: The minimal extent of freshwater environments approximately 2000 years ago. Middle: Around 1900, low salinity environments occurred along the northern margins of Florida Bay and Barnes Sound, typical mid-estuary condition in central regions, and outer estuary near the Safety Valve (tidal pass into Biscayne Bay). Bottom: By 2000, Florida Bay lost typical estuarine zones and is dominated by species that tolerate a wider range of salinities; Biscayne Bay has become more marine.

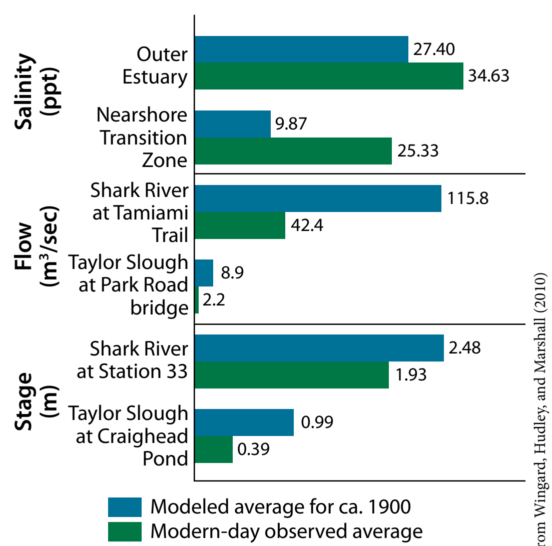
From Wingard, Hudley, and Marshall (2010)

Preserved fauna in the cores show gradual changes over nearly 2000 years and are consistent with a rise in sea level relative to the position of the land. However, by the end of the 20th century, the typical estuarine pattern is not evident, and Florida Bay is dominated by species that tolerate frequently and widely fluctuating salinities. In Biscayne Bay, the environments also shifted during the 20th century. The region near the Safety Valve, where Biscayne Bay opens to the Atlantic Ocean, is dominated by marine organisms, and the estuarine fauna have migrated into areas closer to the shores of the bay.

Historical salinity, based on paleoecologic analysis of cores, has been combined with statistical analysis of hydrology and salinity data collected in south Florida since the 1950s to evaluate the changes that have occurred since 1900. Climatological data and anecdotal information indicate that rainfall patterns and salinity around 1900 were similar to the conditions in south Florida over the past 30 – 35 years. Statistical models (using linear regression equations) were developed from existing data that relate salinity in Florida Bay to freshwater depth and flow at different locations in the present-day Everglades. Salinity estimates based on the paleoecologic data for the beginning of the 20th century are used by the models to estimate the hydrology needed to produce the 1900 salinity values. The flow and depth at different locations in the Everglades are estimated from the 1900 conditions and compared to monitoring data over the past 36 years.

To date, the findings from this analysis indicate flow to the estuaries would be about 1.5 – 2 times greater than the current conditions if the volume and distribution of freshwater discharges to the estuaries of south Florida had not been modified. The statistical models show that observed salinities in the modern-day nearshore transition areas are between 12 – 20 parts per thousand (ppt) higher than estimated salinities from the 1900 data. The stations in Florida Bay that are closest to the Atlantic and Gulf influence have salinities of 5 – 8 ppt higher today than around 1900. The redistribution of freshwater discharges from the Everglades has also created unnatural conditions of lower salinity in extreme northeast Florida Bay, further complicating the understanding of ecosystem changes.

These changes in salinity have affected the diversity, density, distribution, and species composition of the algae, seagrasses, invertebrates, fish, mammals, and wading birds that use the estuaries. The sustainability of the ecosystem and the productive recreational and commercial fisheries are threatened. Scientists agree that freshwater supply and timing that mimic the conditions that existed prior to drainage modifications will result in salinity patterns that will improve the health of south Florida estuarine ecosystems and aid in resiliency in the face of increasing sea level change.



This chart shows differences between the observed modern salinity, flow, and stage (depth of water) at different locations in Everglades National Park and the estimated values based on models using the paleo-salinity values. Modern observed salinity in outer estuary and nearshore (green) is higher than modeled average for 1900 (blue). Flows and water level (stage) at Shark River and Taylor Slough are less today than in 1900.

Geochemical records can be used to determine the history of Florida Bay

Peter K. Swart

In 1986, a large colony of the smooth star coral (*Solenastrea bournoni*) was discovered in Lignumvitae Basin (Florida Bay near Islamorada). Hard corals such as this have annual growth bands that are wider under favorable conditions and narrower under poorer conditions. Thus, the growth bands provide a record of water quality conditions under which the coral grew. This specimen was cored to reveal a growth record from 1825 – 1986. By measuring ratios of carbon and oxygen isotopes in the core bands, changes in salinity over time and other water conditions can be determined.

The extension of the Flagler Railroad from Miami to Key West from 1904 – 1912 blocked the tidal flow of major tidal channels connecting the Gulf of Mexico and the Atlantic Ocean. Observations from coral cores have shown that Indian Key Causeway (Islamorada) in particular blocked a major tidal connection between Florida Bay, an area of limited tidal circulation, and the Atlantic Ocean and changed salinity and circulation patterns in Florida Bay. Some believe that the historical decline in the Bay may be directly linked to this blockage in the tidal exchange.

P.K. Swart - UM/RSMAS

Large smooth star coral cored for use in assessing geochemical records. The inset map (dot) shows the approximate location of the coral in Florida Bay.

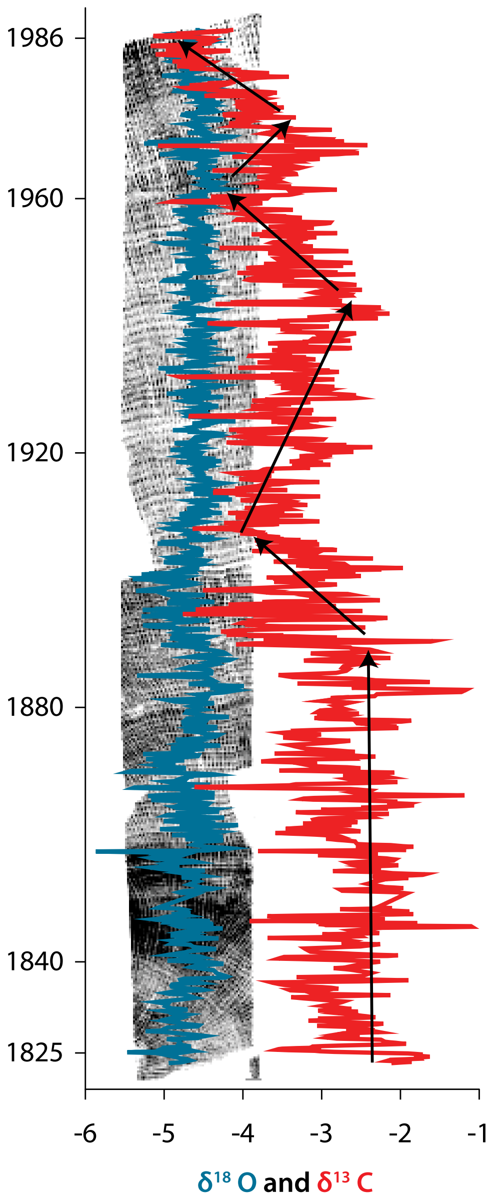
Flagler's Railroad

Henry M. Flagler changed the isolation of the Florida Keys by constructing a railroad from Miami to Key West, but it also blocked tidal exchange between the Gulf of Mexico and the Atlantic Ocean in many areas of the Keys. The railway made Key West a booming deep water port in anticipation of the growth in shipping commerce that would be generated by the opening of the Panama Canal. The 206 kilometer (128 mile)-long railway consisted of 27 km (17 mi) of viaducts and bridges and over 32 km (20 mi) of roadbed fill. With the completion of the railway in 1912, trade with the Caribbean increased, and Key West flourished for 23 years, thus recovering from the loss of the sponge and cigar industries to Tarpon Springs and Tampa, respectively. However, it is believed that the decline of Florida Bay water quality may be linked to a lack of tidal exchange brought about by construction of filled causeways for the railroad bed.

On Labor Day 1935, a major hurricane hit the Upper and Middle Keys, destroying much of the railroad. Hundreds of lives were lost when a 5.2 meter (17 foot) storm surge flooded Islamorada. Afterwards, Monroe County purchased the railroad right-of-way and converted the remaining railway bridges into a series of two-lane bridges for automobiles. The highway from Homestead to Key West was opened for traffic in 1938.

Coral skeletons reveal growth patterns

A cross-section of coral from 1825 – 1986 is shown below, with yearly growth bands superimposed with oxygen (blue) and carbon (red) isotope data. Black arrows depict trends in carbon isotope values. Salinities in the 1800s were somewhat stable and resulted in favorable growth rates of this coral. Construction of causeways impeded the flushing of Florida Bay, contributed to changed ratios of carbon and oxygen isotopes and reduced the coral growth rate. During periods of high hurricane activity, flushing improved, and the coral growth rate increased.



Between 1964 – 1986, no strong hurricanes affected Florida Bay. Hurricane Andrew (1992) passed to the north of Florida Bay and caused a significant amount of organic material to accumulate in the bay. Carbon isotope levels (red) decreased, and coral growth slowed.

Between 1959 – 1964, three strong hurricanes affected Florida Bay causing the carbon isotopic composition to become more positive.

After 1945, the number of hurricanes declined, the carbon isotopic value decreased once more, and coral growth slowed again.

After 1910, the carbon isotopic values gradually moved toward more positive values. This is believed to arise from numerous hurricanes in this period that caused increased exchange between Florida Bay and the Atlantic Ocean between 1910 – 1945.

The largest decrease in the carbon isotopic rate occurred between 1905 – 1910, coincident with the construction of the overland railway to Key West. The oxygen isotopic composition (blue) shows a slight increase over this period, indicating slightly higher salinity values, and coral growth declined.

The carbon isotopic composition decreased from about -2 at the start of the records to -5 by 1986. This decrease is a result of the increased oxidation of organic material within Florida Bay and less exchange with the open ocean. The oxygen isotopic composition, which is linked to salinity, shows no long-term trend but is more variable prior to 1910.

Coral annual growth bands can be revealed using X-ray and oxygen (blue) and carbon (red) isotope ratios measured using a mass spectrometer.

Climate change will have several potential impacts to south Florida

Harold Wanless, William L. Kruczynski, and Pamela J. Fletcher

NOAA

Temperature extremes

At continental, regional, and ocean basin scales, numerous long-term changes in weather and climate have been observed. These include increases in arctic temperatures and accelerating ice loss; widespread changes in precipitation amounts, ocean temperature, and salinity; wind patterns; and increased extreme weather, including droughts, heavy precipitation, and heat waves. Observations since 1961 show that the average temperature of the global ocean has increased from the surface to depths of at least 3000 meters (9800 feet). Excessively hot or cold water temperatures can result in death of organisms that are unable to move, such as corals, seagrasses, and other benthic organisms.

J.W. Porter - UGA

Ocean water chemistry

Carbon dioxide (CO_2) in the atmosphere dissolves in ocean waters, creating carbonic acid. Rising levels of CO_2 are making ocean water more acidic. Increased acidity makes it harder for coral polyps and other calcareous organisms to build their shells, may cause bleaching, and affects survival of coral larvae after settlement. There has been a steady drop in calcification rates by marine organisms over the past 20 years. Currently, atmospheric CO_2 levels are 387 parts per million (ppm), rising from 305 ppm in 1960. When CO_2 levels in the atmosphere reach about 500 ppm, calcification by sea life may diminish dramatically.

W. L. Kruczynski - EPA

Sea-level rise and coastal erosion

Global warming is resulting in rising sea levels due to thermal expansion of the oceans and melting of ice sheets. Deepening water will flood mangrove swamps and other coastal wetlands, and their ability to keep pace with rising waters is uncertain. Low-lying developed areas will be flooded, and property damage and loss will be immense. Coastal bays will become increasingly marine. Coasts will become more and more eroded and dissected by storms. Increased turbidity and nutrients from coastal erosion will further stress coral reefs and other benthic communities.

NOAA

Weather and climate patterns

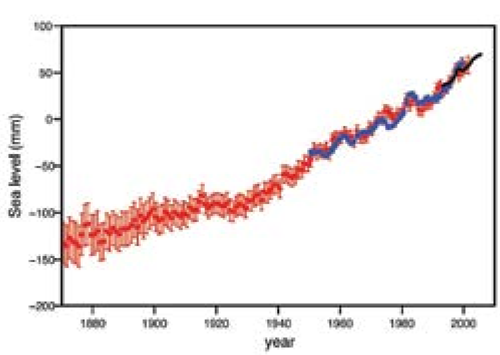
There is observational evidence of an increase in intense tropical cyclone (hurricane) activity in the North Atlantic since about 1970. A list of the 11 worst hurricanes to hit Florida in the past century includes five in the past 17 years. An increase in the severity of hurricanes will result in damage to developed areas and natural communities, particularly as sea level rises and contributes to increased flooding. Mangrove forests severely damaged by hurricanes are very slow to recover. Coral reefs already weakened by bleaching, disease, or pollution will be vulnerable.

Sea-level rise will have dramatic impacts on south Florida's landmass

Harold Wanless

Although some people continue to debate the issue, overwhelming scientific evidence supports the fact that climate is changing at an unprecedented rate because of human-induced warming. Sea-level rise is one of the most profound consequences of climate change. There is still some debate about how fast sea level will rise, but most scientists agree that there will be significant sea-level rise this century. Unless atmospheric and oceanic warming are quickly reversed, there will be catastrophic sea-level rise in the coming centuries. A rising sea will inundate not only south Florida, but also a significant portion of peninsular Florida. With each year that humankind does not reverse the causes of global warming, the coming catastrophic impacts on human and natural environments become increasingly likely and less reversible.

Greenhouse gases are driving human-induced global warming and include carbon dioxide, methane, nitrous oxide, and chlorofluorocarbons. These gases act as a blanket around the globe, trapping back-radiating solar energy. The most abundant greenhouse gas is carbon dioxide; its main source is from burning fossil fuels (e.g., coal, oil, and natural gas).



Beginning in the 1930s, the rate of sea-level rise dramatically increased primarily due to warming and thermal expansion of the oceans. The present rate of sea-level rise in south Florida is about 30 cm (1 ft) every 100 years. Sea-level rise is accelerating due to melting polar ice.

Lag time

Even if humans stopped putting carbon dioxide into the atmosphere today, sea-level rise will continue because of the long lag period for decreasing the effects of emissions. Lowering the carbon dioxide levels in the atmosphere from the current level of 387 parts per million (ppm) to below 325 ppm will lower the heat imbalance between the atmosphere and the ocean but will probably not slow the first 90 – 150 cm (3 – 5 ft) of sea-level rise.

Florida has experienced sea-level rise and fall throughout geological time. About 125,000 years ago, the peak of the previous interglacial period, sea level was 6 meters (20 feet) higher than today, and most of south Florida was underwater. About 18,000 years ago, the peak of the subsequent Ice Age, sea level dropped 128 m (420 ft) below present-day levels. At that time, Florida and Biscayne Bays were high and dry. Sea level has been slowly increasing a few centimeters per century for the past 2000 years, but since the 1930s, the rate has dramatically increased. The current rate of rise in Florida is 30 centimeters (1 foot) every 100 years, about the same as the global rate.

There are two main causes of accelerated sea-level rise: melting of the polar ice sheets and thermal expansion of the oceans. Since the mid-1990s, warmed ocean water is accelerating the melting of the Greenland and Antarctic Ice Sheets, causing an increased rate in sea-level rise that is higher than earlier projections. This has sped the loss of the Arctic summer pack ice, the "refrigerant" of the Arctic. A portion of atmospheric heat is transferred to the oceans, which then become warmer and expand. Sea-level rise will accelerate through this century and beyond and is expected to reach 90 –180 cm (3 – 6 ft) by 2100.

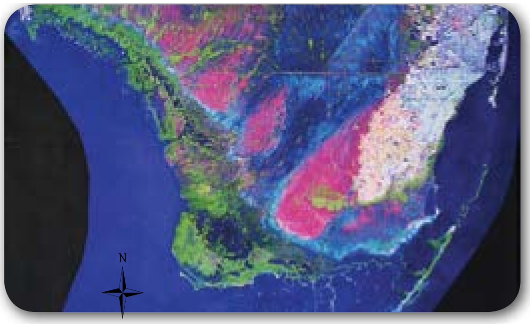
What does this mean for south Florida? The Miami-Dade County Climate Change Task Force provided more accurate predictions of rates of sea-level rise and their local consequences. In 2008, the Task Force predicted a rise of 50 cm (1.5 ft) in the next 50 years and a total of 90 – 150 cm (3 – 5 ft) by the end of the century. The upper projection has recently been raised to 180 cm (6 ft). Whatever the sea level is at the end of the century, it is important to understand that the rate of sea-level rise will continue to accelerate. For example, if sea level has risen 150 cm (5 ft) by 2100, the rate of sea-level rise will be 30 cm (1 ft) per decade.

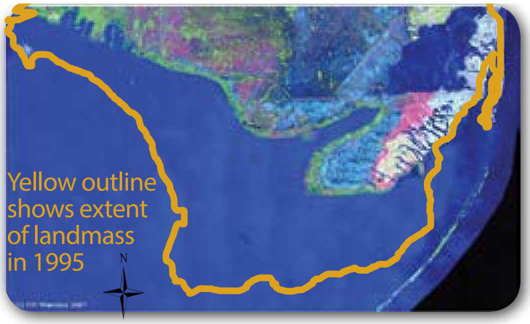
A 60 cm (2 ft) rise in sea level will result in the Turkey Point Nuclear Power Plant becoming an island in a combined Biscayne-Florida Bay. All coastal wetlands will be flooded, and the coastal mangrove community will have shifted north to about Tamiami Trail (U.S. 41 between Miami and Naples). Only about 40% of presently developed Miami-Dade County will be above mean high water with a sea-level rise of 180 cm (6 ft), and marine waters will extend nearly to Lake Okeechobee.

Restoring the Everglades may slow the process of sea-level rise in south Florida. The Everglades historically has been drained over the past century, resulting in a loss of organic (peat) soils. As a result, the elevation of much of the Everglades has decreased. The loss of peat soils has lessened the ability of the Everglades to serve as a buffer to saltwater intrusion with rising seas, maintain a freshwater head (elevation above sea level) to recharge the drinking water aquifer, and stabilize the shoreline.

Meaningful restoration efforts include the reestablishment of a reliable southward flow of freshwater that can help rebuild peat soils. Research is needed to quickly learn how to most rapidly build resilient peat substrates that contribute to a healthy wetland environment. These restoration efforts will prolong both the survival of the Everglades and the time that the surficial, unconfined, freshwater aquifer is available for use. At the same time, efforts to reduce the levels of greenhouse gases in the atmosphere must be aggressively pursued.

The hurricanes of 1935, 1960 (Donna), and 1992 (Andrew) destroyed vast amounts of mangrove forests in south Florida. Large areas were converted to open water because of rapid erosion, and the subsidence of peat, combined with rising sea level, prevented the recovery of the mangrove community. With accelerating rates of sea-level rise, coastal mangrove wetland destruction during storms will occur over broad geographic areas. Restoration of storm-damaged wetlands is required to prolong the survival of coastal wetlands and protect sources of fresh groundwater.





A comparison of south Florida in 1995 (left) and south Florida with a sea-level rise of +120 cm (+4 ft) (right). Note the losses of all of the fringing mangrove coastline on the southwest coast, much of the southern Everglades, and all of the islands in Florida Bay. Most dramatically, the majority of developed Miami-Dade County and the Upper Keys will be either inundated or so low that they will be flooded by heavy rains and tropical storms. The Upper Keys will also be significantly reduced in size. South Florida will become an increasingly risky and inconvenient place to live.

Estimates of ecological and economic consequences of sea-level rise on the Florida Keys are staggering

Chris Bergh

Climate change is happening at a rate unprecedented in modern times. Some symptoms of climate change include:

- Certain species of migratory birds are now wintering further north than they did in the recent past;
- Glaciers around the world are shrinking;
- The amount of ice in the Arctic Ocean has significantly declined; and
- Sea level is rising, which is one of the more predictable consequences of climate change.

Although estimates vary, it is likely that sea-level rise will be at least 50 centimeters (20 inches) by the end of this century and could be twice that amount or more. To predict future impacts of sea-level rise on the environment and economy of the Florida Keys, The Nature Conservancy combined 2007 high resolution topography data for Big Pine Key, lower resolution data for the entire Keys, and Monroe County tax data using Geographic Information System computer software. "Bathtub modeling," a digital simulation of rising waters, was conducted using five published sea-level rise scenarios for the year 2100, ranging from 18 – 140 cm (7 – 55 in).

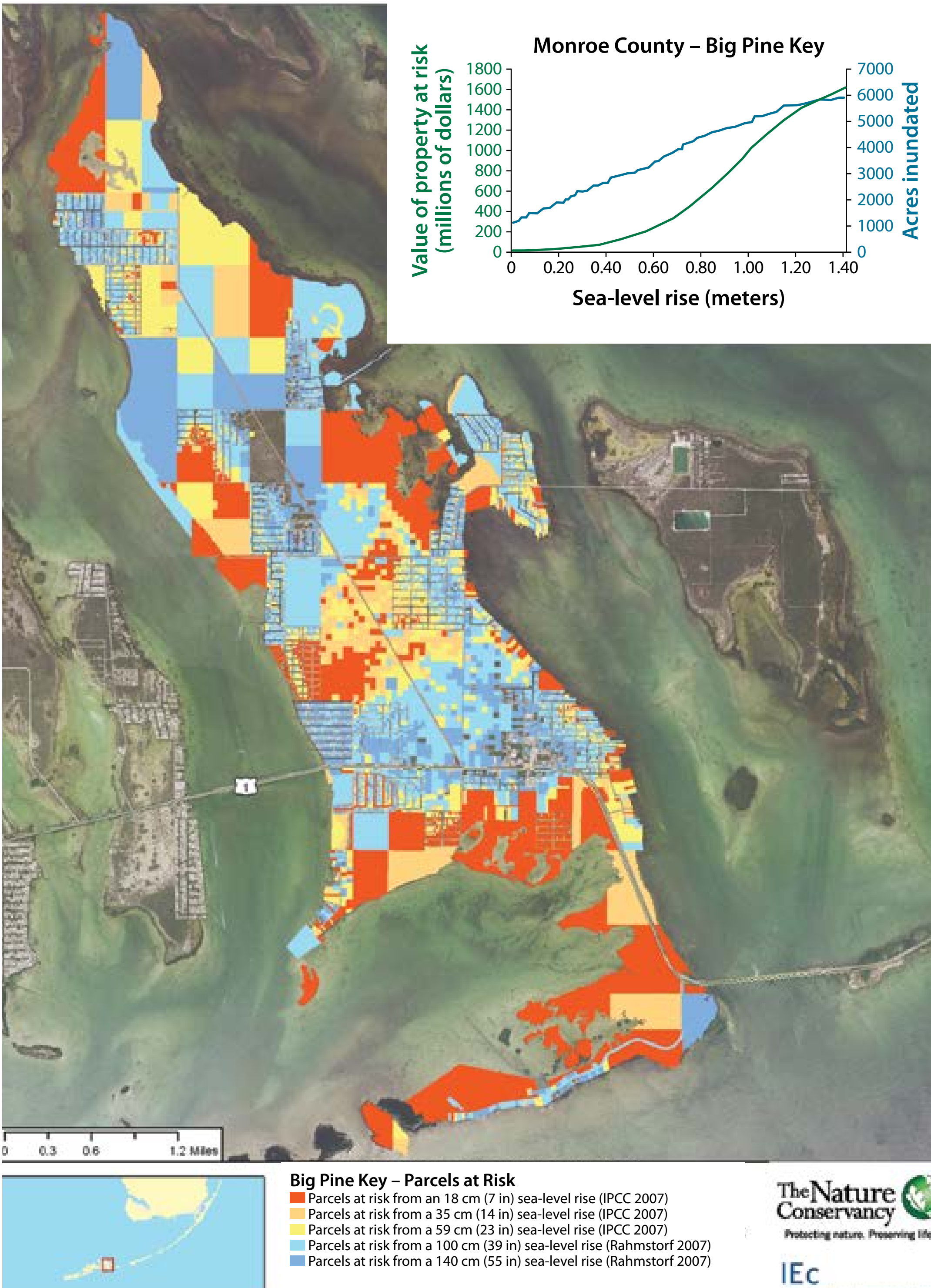
The high-resolution topography data enabled a detailed prediction of future shorelines, distribution of major terrestrial habitats, and property value losses for Big Pine Key. In every scenario, the island became smaller, marine and intertidal habitat moved upslope at the expense of terrestrial habitat, and property values diminished. In the best-case scenario (i.e., 18 cm [7 in] sea-level rise), 744 hectares (1840 acres) (34%) of Big Pine Key was flooded by the sea, resulting in the loss of 11% of the upland habitats on the island. This degree of inundation would displace native species dependent on upland habitat and threaten $40 million of property values. In the worst-case scenario (140 cm [55 in]), 2407 ha (5950 ac) (96%) of the island was inundated, resulting in the loss of all upland habitat and $1.6 billion in property values.

This modeling exercise demonstrates that in the next one to three centuries, sea-level rise is likely to jeopardize most, if not all, of the terrestrial plants, animals, and natural communities of the Florida Keys while creating new marine habitat. Developed areas and human communities will experience negative impacts, including lost property values.

Minimizing the consequences of sea-level rise will require marked decreases in greenhouse gas emissions and deforestation, the main causes of climate change. Also essential are careful planning and implementation of local actions to help terrestrial natural areas, native species, development, and human communities adapt to inevitable change.

	Lower Keys			***Florida Keys***		
Sea-level rise scenario	**Property value at risk (billions)**	**Hectares (ha)**	**Acres (ac)**	**Property value at risk (billions)**	**Hectares (ha)**	**Acres (ac)**
IPCC 18 cm	$2,610,000,000	4,450	11,000	$11,000,000,000	23,800	58,800
IPCC 35 cm	8,790,000,000	19,910	49,200	18,700,000,000	42,900	106,000
IPCC 59 cm	11,000,000,000	22,000	54,400	21,900,000,000	46,500	115,000
Rahmstorf 100 cm	13,000,000,000	22,800	56,300	26,700,000,000	50,200	124,000
Rahmstorf 140 cm	15,800,000,000	23,500	58,000	35,100,000,000	57,500	142,000

Year 2100 property value at risk and acreage lost to inundation by sea-level rise for the Lower Keys and for the entire Florida Keys predicted by a model using the best-available elevation data in 2009. IPCC = Intergovernmental Panel on Climate Change 2007; Rahmstorf = Rahmstorf 2007.



Industrial Economics, Incorporated and The Nature Conservancy

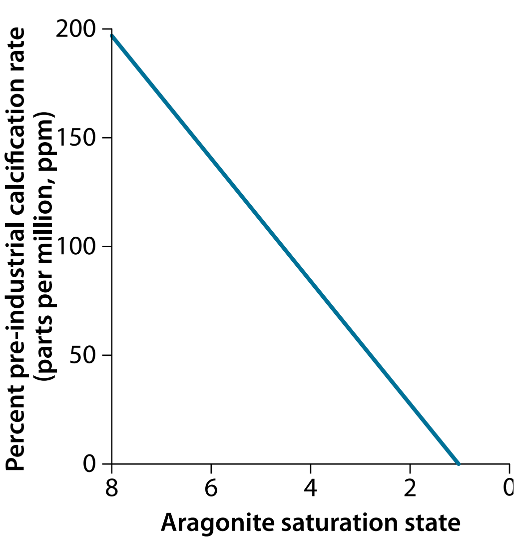
Aerial photograph of Big Pine Key with overlay showing cumulative land parcels at risk under various scenarios of sea-level rise. Sea-level rise scenarios tested are 18 cm (7 in) red; 35 cm (14 in) orange; 59 cm (23 in) yellow; 100 cm (39 in) light blue; and 140 cm (55 in) dark blue. Line graph inset: Green line on graph is an estimate of value of property at risk. Blue line is the number of acres inundated by seawater.

Ocean acidification may be a threat to the marine ecosystem

Christopher Langdon

Carbon dioxide (CO_2) is one of the most important gases in the atmosphere. It affects the radiant heat balance of the Earth and the calcium carbonate equilibrium of the oceans. Cores in glacial ice show that for 650,000 years prior to the Industrial Revolution, atmospheric CO_2 concentrations remained between 180 – 280 parts per million (ppm). Increased burning of fossil fuels, cement production, and changes in land use are causing atmospheric CO_2 to rise at increasing rates. The atmospheric CO_2 concentration in 2008 was about 387 ppm and is expected to continue to rise by about 1% per year. This increase is about 100 times faster than occurred over the past 650,000 years and possibly the past 25 million years.

"Ocean acidification" is the name given to the ongoing decrease in the pH of the oceans caused by their uptake of anthropogenic CO_2 from the atmosphere.



This graph is a summary of the growth of 12 coral species at different carbonate (aragonite) saturation states. Data demonstrate that as saturation declines (with decreasing pH) from a present-day value of 3.8 – 4.0, the calcification of corals declines significantly and will stop completely if saturation reaches 2.0 or below.

Carbonate chemistry

Changes in the chemistry of the ocean can have major impacts on organisms that precipitate calcium carbonate from seawater to make shells. As the pH of the seawater changes, the ability to precipitate calcium carbonate (calcification rate) is changed. As atmospheric carbon dioxide increases, more carbon dioxide dissolves in seawater, resulting in a lower pH. Lowering the pH decreases the amount of calcium carbonate that can be dissolved in seawater (saturation state). Decreasing the saturation state can lead to a decreased ability in marine organisms to produce shells from seawater because the carbonate ions that bond with calcium are less available.

About a third of the excess CO_2 released by anthropogenic activities has been stored in the oceans. The ocean is well buffered, but the present rate of input of CO_2 greatly exceeds the rate at which natural processes can neutralize the carbonic acid that is formed when the CO_2 from the atmosphere dissolves into the ocean. As a result, the ocean is becoming progressively more acidic (lower pH), and the saturation state of carbonate minerals is declining.

Carbonate minerals are used to form the supporting skeletal structures (biocalcification) of many groups of marine organisms, including corals. Controlled laboratory experiments on the effects of increased CO_2 conditions on biocalcification have documented that the calcification rate of many organisms decreases with a slight reduction in pH. Extrapolation of these results from the laboratory to the real world suggests that calcification rates in the oceans will decrease up to 60% within the 21st century.

What does this mean for corals and other marine organisms, such as calcareous algae, mollusks, and echinoderms, that have calcium carbonate skeletons? Not much is known about how decreased calcification will affect biological functioning or organism survival. However, it is widely accepted that marine organisms with calcareous skeletons will be significantly stressed. Analyses of coral skeletons have recently been reported to show that coral growth rates have declined by 11% – 21% in just the past 16 years. Other studies have shown that pH decreases of as little as 0.1 – 0.2 pH units result in a 50% – 78% reduction in postsettlement growth of mustard hill coral (*Porites astreoides*) larvae. In a world where the balance between production and loss of carbonate on many reefs is believed to be closely balanced and where replacement of new corals on many reefs is not keeping up with mortality, a reduction in fitness due to ocean acidification may have significant impacts. Acidification may not kill corals directly, but it does result in slower development of coral larvae into juvenile colonies and slower development of juvenile colonies to sexually mature colonies. Also, it is known that increased CO_2 in the atmosphere is raising the average temperature of the oceans, and warmer waters mean increased incidence of coral bleaching. Thus, it is possible that acidification may play a synergistic role in the lack of recovery of many reefs. Further research is required to quantify the impacts of increasing acidity on the structure and function of the south Florida marine ecosystem.

B. Fluech - FSG

Wikimedia

J. Luo - UM/RSMAS

M.A. Moe Jr. - MML

A change in ocean chemistry could impact the way marine organisms, such as the bay scallop (top left), hard and soft corals (bottom left), queen conch (top right), and the long-spined sea urchin (bottom right), build their skeletal structures.

Hurricanes and tropical storms are regular features in south Florida

William L. Kruczynski, Pamela J. Fletcher, and Neal M. Dorst

Hurricanes and tropical storms are regular summertime features in south Florida. The name "hurricane" comes from the Caribbean Taino Indian god, Huracan. Hurricanes develop over warm ocean waters from weak disturbances where moist air gets drawn into their low pressure areas. In many south Florida storms, the initial disturbance forms off the west coast of Africa, but storms can also develop from low pressure disturbances originating in the tropical Atlantic or Caribbean. The Coriolis effect causes winds to spiral inward and counterclockwise in the northern hemisphere. Within the low pressure system, rising moist air condenses as it cools, produces rain, and releases heat to the atmosphere, causing the air pressure to decrease further, which pulls more moist air into the system at the surface of the ocean. The storm intensifies as long as these processes continue. As a storm passes over land or cool water, it loses its source of energy and dissipates.

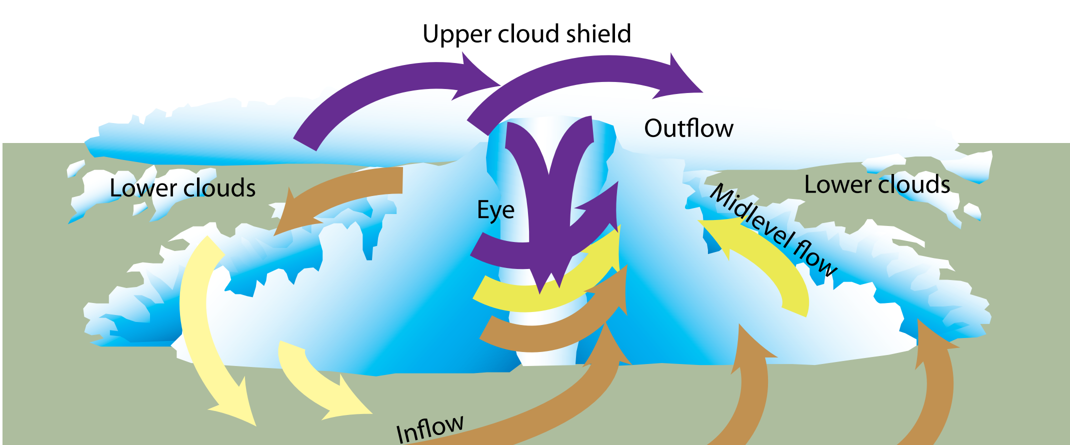
Saffir-Simpson Hurricane Wind Scale	
1	74 – 95 mph
2	96 – 110
3	111 – 130
4	131 – 155
5	155+

The number of tropical storms that strike Florida varies from year to year but averages about 1.7 storms annually. The chances of hurricane-force winds striking Florida each year varies from 1:100 for Jacksonville to 1:7 for Miami and Key West. The longest period since 1885 without a major hurricane was 9 years, between 1951 – 1959.

Every storm is different, and it is hard to compare storms. Here are some of the worst to hit south Florida.

1919 Atlantic-Gulf Hurricane

This was the most powerful storm in Key West history. It was the only hurricane known to form in the Atlantic that year. It killed more than 800 people.



Hurricane structure and formation.

1926 Great Miami Hurricane

"The blow that broke the population boom" was described at the time as the most destructive hurricane ever to strike the United States. Storm surge of 4.6 meters (15 feet) was reported in Coconut Grove as the eye passed over Miami. Many of the 800 people killed had stepped outdoors during the lull of the passing eye and were swept away when the opposite side of the eyewall passed over the area.

1928 San Felipe-Okeechobee Hurricane

This hurricane came ashore near Palm Beach. When the eye passed over Lake Okeechobee, shifting winds pushed the lake waters against the southern dikes, causing them to fail, and sweeping away homes. Over 1800 Floridians perished.

1935 Florida Keys Labor Day Hurricane

This Category 5 hurricane struck the Middle Florida Keys, destroying the railroad and killing 408 people. Barometric pressure readings from Long Key reflect this to be the most intense hurricane on record in the region.

1960 Hurricane Donna

This Category 4 storm hit the Middle Florida Keys and Fort Myers. Heavy rainfall and storm surges impacted south Florida.

1964 Hurricane Cleo

This Category 2 storm hit Key Biscayne and passed over Miami, Opa-locka, West Hollywood, and Fort Lauderdale. The hurricane caused extensive power outages and water damage that impacted much of the southeast Florida coast.

1965 Hurricane Betsy

The area between Key Largo and Miami was impacted by this Category 3 storm. The storm appeared to be headed to South Carolina; however, it stopped 570 kilometers (350 miles) east of Jacksonville before heading back to south Florida.

1992 Hurricane Andrew

Andrew hit Homestead as a Category 5 storm and caused a 5.2 m (17 ft) storm surge. It is the second costliest storm in the mainland U.S. history.

2004 Hurricane Charley

This storm passed over the Dry Tortugas (177 km [110 mi] per hour winds) and then hit southwest Florida as a Category 4. Most of the damage from Charley was caused by high winds and tornadoes.

2004 Hurricane Frances

This was one of several large hurricanes that hit south Florida in a period of 6 weeks. It was a slow-moving, super-sized storm that covered the entire state of Florida. Upon making landfall near Stuart, the storm produced heavy rainfall and strong winds.

2004 Hurricane Jeanne

This Category 3 storm hit Stuart shortly after Frances. Impacts launched existing piles of storm debris and further weakened buildings, causing additional damage in the area.

2005 Hurricane Katrina

This storm hit the border of Miami-Dade and Broward Counties before moving westward to wreak havoc in Louisiana and Mississippi. Rainfall over southern Florida was estimated between 25.4 – 35.6 cm (10 – 14 in) and flooding and wind damage was extensive. The storm caused $81 billion in damages in the United States.

2005 Hurricane Wilma

It took 5 hours for this storm to pass over southern Florida, entering at Cape Romano and exiting north of Palm Beach as it changed from a Category 3 to a Category 2 hurricane. The storm caused five deaths in Florida and damages estimated at $16.8 billion.

Major hurricanes can have major impacts on marine environments

William L. Kruczynski and Pamela J. Fletcher

The loss of human life and property is well documented for major hurricanes. However, the environmental effects of hurricanes are less well-known.

On August 24, 1992, Hurricane Andrew struck near Homestead, Florida just before high tide, resulting in a storm surge of 5.2 meters (17 feet) on the Atlantic coast and 4.6 m (15 ft) on the Gulf coast. It was a relatively dry storm and resulted in approximately 5 centimeters (2 inches) of rain. Its path over land was approximately 100 kilometers (62 miles) long, and it partially or completely defoliated vegetation over a 50 km (31 mi)-wide swath. However, Andrew was a very fast moving storm, which may have reduced its potential damage to the marine environments.

Hurricane Andrew affected nearshore water quality by increasing nutrients from runoff and disturbing bottom sediments. Increased concentrations of phosphorus and nitrogen resulted in phytoplankton blooms and low levels of dissolved oxygen after the storm. Depleted oxygen levels in waterways resulted in the death of an estimated 7 million fish. In hardbottom communities, sponges, corals, and sea whips were sheared from their substrate and deposited in extensive wracks of debris along shorelines. Juvenile Caribbean spiny lobsters, normally found under sponges and in coral crevices in central Biscayne Bay, disappeared. Minimal losses of seagrasses were documented after Andrew, but seagrass meadows are not immune from storm damage. For example, three of the 30 permanent seagrass monitoring stations in the Florida Keys National Marine Sanctuary were deeply buried by sandy sediment during Hurricane Georges (1998); the seagrasses have yet to recover.


FKNMS

Pillar coral overturned by Hurricane Andrew in the Florida Keys.

Hurricane Wilma destroyed a large area of mangrove forest near the mouth of Shark River, southwest Florida.

Hurricanes and tropical storms can be beneficial to coral reefs by breaking branching corals (*Acropora cervicornis* and *Acropora palmata*) into pieces, each of which can grow and form a new colony. However, the gains achieved by asexual proliferation of branching corals are likely to be offset by storm scouring and sediment smothering of other corals and turning over coral heads.

Hurricanes have been a central feature in the evolution of subtropical and tropical ecosystems; however, the natural ecosystems are not adapted to withstand additional impacts due to anthropogenic sources. For example, approximately 95,000 liters (25,000 gallons) of gas and oil were spilled into Biscayne Bay during Hurricane Andrew. The most severe damage noted to coral communities was from lobster and crab traps that smashed coral heads and reefs. A ship sunk as an artificial reef broke free and destroyed natural coral reefs as it was carried by strong waves generated by the hurricane. During heavy rains, canals rapidly drain freshwater to coastal areas, which results in rapid drops in salinity and untold impacts to marine biota.

Two weeks after Hurricane Andrew passed, the mangroves within the path resembled a deciduous forest in winter. Many trees that were completely defoliated have not recovered. At Highland Beach, where the hurricane eye left the west coast of Florida, more than 85% of the mangrove trees were blown over and uprooted.

Hurricane Donna (1960) spread the seeds of Australian pine (*Casuarina equisetifolia*), an invasive exotic plant, along the west coast of Everglades National Park, and the resulting vegetative overgrowth posed a threat to turtle nesting areas. Open patches in mangrove forests are threatened by the invasion of Brazilian pepper (*Schinus terebinthifolias*) because it can occupy open areas more quickly than native mangroves. In short, hurricanes may change the balance in favor of nonnative invasive vegetation that can have long-lasting impacts on the ecosystem.

African dust is an airborne pollutant in south Florida

Eugene A. Shinn

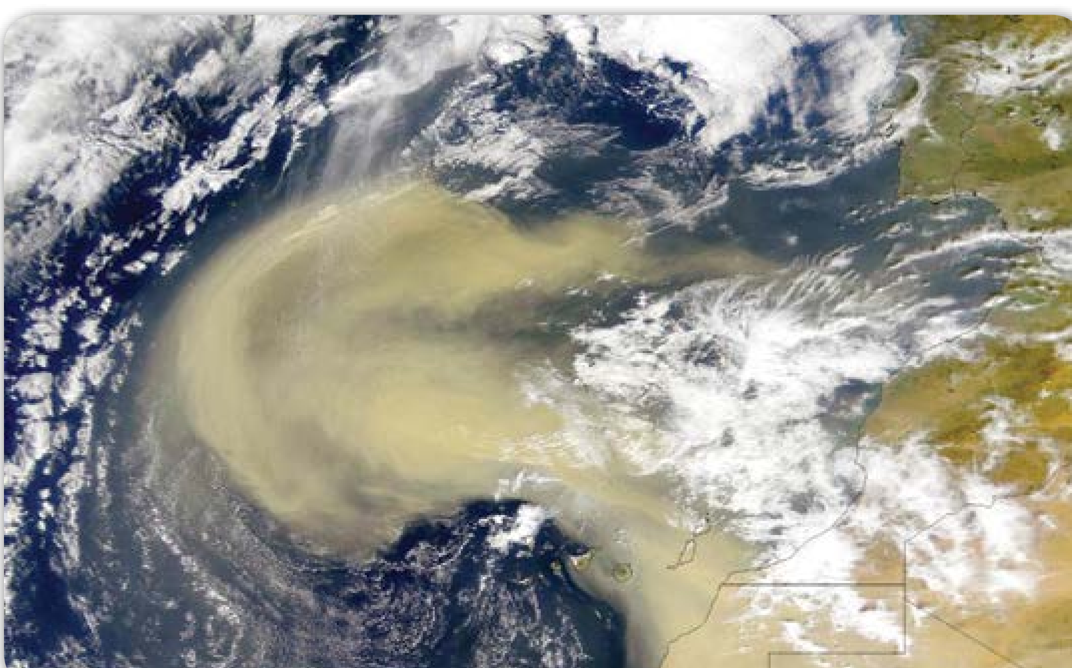
It is a small world

African dust is transported to Florida mainly during the summer months by trade winds blowing across the Atlantic Ocean. During the winter months, the dust is transported to South America where it has been shown to nurture the Amazon rainforest. Most dust clouds are transported during positive phases of the North Atlantic Oscillation (NAO), the meteorological equivalent of the Southern Oscillation in the Pacific called the El Niño. Positive NAO reduces rainfall in North Africa and accelerates trade winds. Major episodes of dust transport across the Atlantic occurred during NAO events in 1973, 1983, and 1997.

Why is this important?

African dust is a suspect in the Caribbean-wide loss of corals and other marine life. The dust has been found to contain DDT, a pesticide that is used legally in Africa but banned in the United States because it accumulates in aquatic food chains. Microbiologists captured dust on sterile filters in Africa, over the Atlantic Ocean, and in Florida during dust events and cultured bacterial and fungal spores present in the dust. To date, more than 200 microbes that ride the dust have been identified, including well-known human, animal, and plant pathogens.

Medical records show that asthma attacks in the Caribbean have increased 17 times since 1973 and that 25% of children in the eastern Caribbean today have asthma. The connection of asthma with African dust has not yet been medically proven, but it is known that people living in the eastern Caribbean start coughing during dust events and must frequently clean dust from boats, docks, and drinking water cisterns.



NASA

Major dust storm leaving the west coast of North Africa in February 2000.

E.A. Shinn - USGS

African dust in the atmosphere causes red-colored sunsets, such as this sunset over the Seven Mile Bridge, Florida Keys, on August 1, 2008.

Impacts of African dust

African dust may affect reefs by depositing nutrients, pollutants, or pathogens that:

- Interfere with the immune system of corals;
- Interfere with some stage of coral reproduction;
- Activate disease-causing microbes present in the reef environment;
- Trigger rapid increases in pathogens; and
- Fuel cyanobacteria, macroalgae, and phytoplankton growth.

What is different today?

Geological evidence from the past million years shows that African dust has periodically been deposited on Florida shores, especially during glacial periods when the air was extremely dry. If dust today is a problem to the marine ecosystem, did it have effects on ecosystems in the past? No one knows, but what is certain is that there were no pesticides, phosphate mining, or mercury mining in North Africa in geological times. Also, North Africa lacked the human population that exists there today. Along with the advent of vehicular traffic, open fire, waste disposal, and deforestation to feed the ever-expanding human and animal populations, the content of African dust is undoubtedly different today than in the past. An increase in domestic animal droppings and raw human sewage has resulted in a larger pool of microbes that can be carried across the Atlantic Ocean. All of these changes, including climate change, have loosened the delicate desert soils and have made them far more transportable by winds than in the past.

T. Hinson

African dust in the atmosphere can cause halos around clouds in south Florida.

There has been a loss of megafauna from south Florida waters

Dalal Al-Abdulrazzak

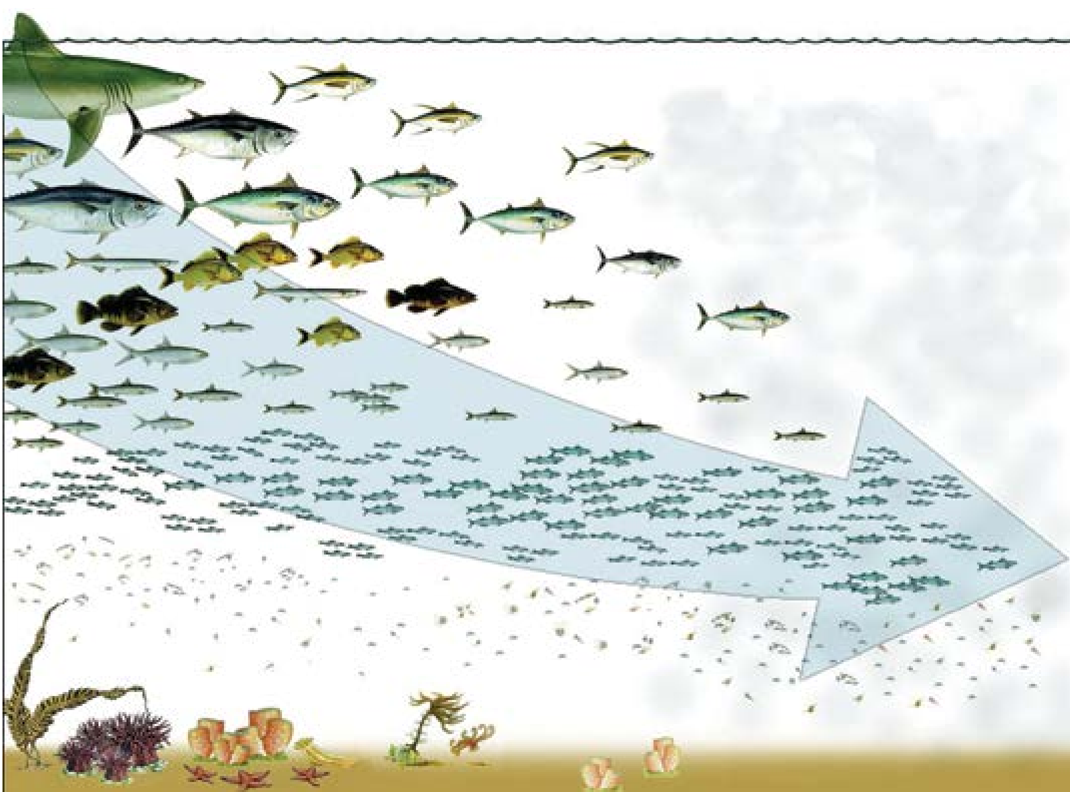
Large animals, or megafauna, such as manatees, sawfish, large sharks, and sea turtles, are all but extinct from south Florida. Their high numbers, ease of capture, and large size appeals to humans. Megafauna are especially vulnerable to overharvesting due to their slow maturity and low number of offspring. Female manatees, for example, reach sexual maturity between 6 – 10 years of age, after which they only bear a single offspring every 2 – 5 years.

After the near elimination of large tertiary consumers, people turned their attention to the secondary, and even primary, consumers of the sea. Unlike on land, where consumers at the top of food chains (e.g., lions, tigers) have never been an important part of the human diet, at sea, humans were attracted first to large predators (e.g., sharks, tuna, swordfish).

Megafauna are ecologically important to the marine environment not only

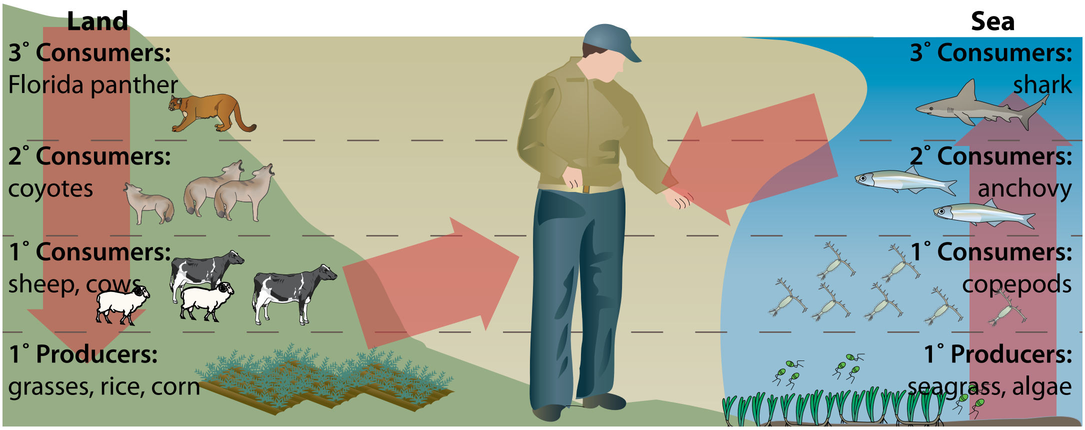
J. Luo - UM/RSMAS

Large animals (megafauna) that were commonly found in south Florida, such as sea turtles, are found in significantly fewer numbers or no longer exist.



Sea Around Us Project

Because most megafauan have been overfished in the past, people today are forced to fish farther and farther down the food chain, harvesting smaller and smaller sized species.



Human energy pyramid on land and sea. Humans gain most food energy from terrestrial primary producers, such as rice and corn, and primary consumers, such as cows and sheep. From the sea, humans harvest top predators in the marine food web, such as swordfish, tunas, sharks, and mackerels.

because of their place at the top of the food web, but also because of their specific physical and biological functions. For example, the loss of manatees and sea turtles has severely altered seagrass grazing, food web structure, and productivity in adjacent ecosystems. Nearshore marine environments today are very different from when manatees and sea turtles were common.

Today, small fishes and invertebrates dominate the coral reefs, but their presence cannot fully compensate for the loss and the unique role large vertebrates play in an ecosystem. Dr. Jeremy Jackson, a prominent marine ecologist, wrote,

"Studying grazing and predation on reefs today is like trying to understand the ecology of the Serengeti by studying the termites and the locusts while ignoring the elephants and the wildebeests."

J. Luo - UM/RSMAS

With the loss of large marine animals, small fishes typically dominate nearshore marine environments.

Overfishing has reduced fish stocks in south Florida

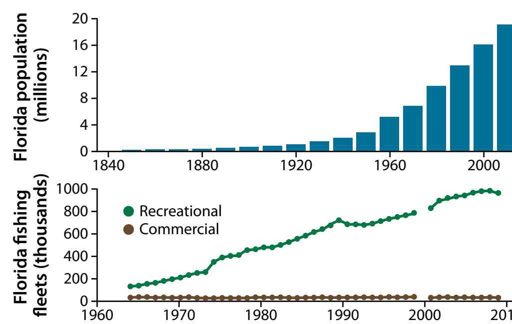
Jerald S. Ault

South Florida is home to a species-rich tropical marine ecosystem that supports a multibillion dollar tourist economy. The diverse fish community of the reefs and associated habitats is influenced by complicated biological and physical interactions, not the least of which is commercial and recreational fishing pressure. It is not surprising that catches of prized grouper and snapper have declined in numbers and size from historical levels given the 658% explosive growth in the number of recreational fishing boats, based on boater registrations, since the mid-1960s. Also, better design and the addition of modern hydroacoustic, navigation, and communication devices have resulted in greater fishing prowess than vessels and fishing techniques used in the recent past.

Monroe County Public Library

Fish stocks in the Florida Keys could not be sustained at historical fishing landings.

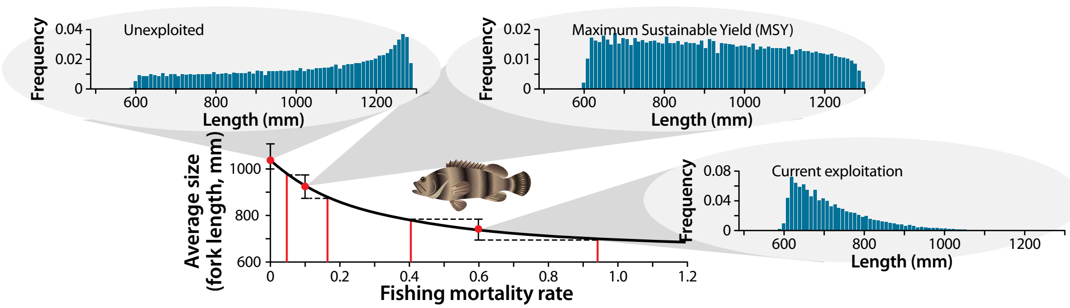
A comprehensive 26-year study (1979 – 2005) was performed to examine the effects of fishing and to establish a baseline of the status of the multi-species fishery in the Florida Keys. The results contributed to an accurate evaluation of the management actions in the Florida Keys National Marine Sanctuary. The average size of fish from visual observations at reefs throughout the Keys was compared with sizes from head boat catches to develop an indicator of the stock status for each of the fish species observed and caught. Heavy fishing pressure successively eliminates older, more reproductively active size classes and reduces the average size of fish over time, making the stock younger (juvenescence). Smaller fish have a substantially lower reproductive output compared to larger fish. Exploited species are considered overfished when the Spawning Potential Ratio (SPR) (ratio of a fished to an unfished stock) is reduced to 30% or less.



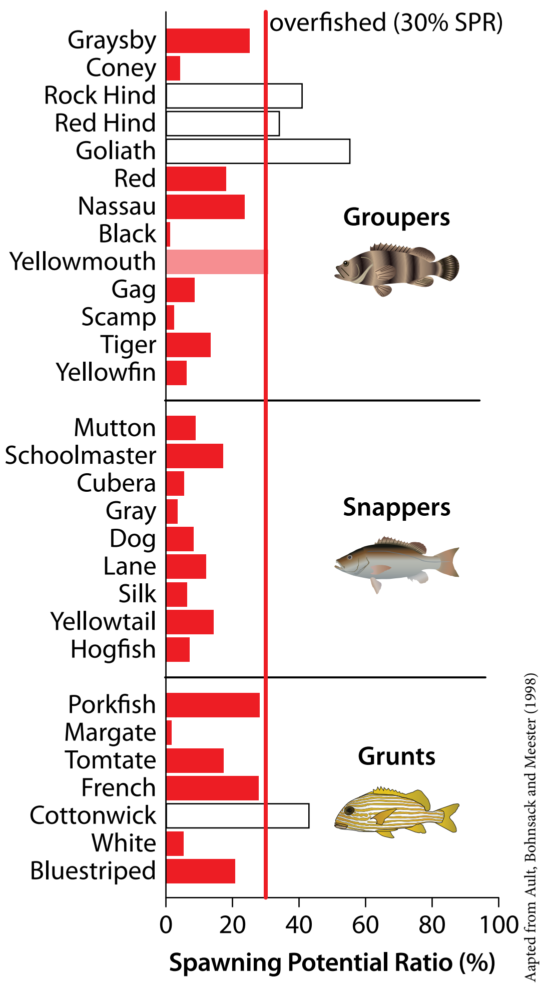
Aapted from Ault, Bohnsack, and Meester (1998)

The human population in Florida (top graph) and the number of registered fishing boats (bottom graph). The number of registered recreational fishing vessels in Florida has increased 658% since 1964.

Although 46 reef fish species were seen or captured by head boats, data for only 29 species were abundant enough for statistical comparisons. The data from the two independent sources were highly correlated for grouper, snappers, and grunts. It was found that the average size for many of the economically important reef fish populations was marginally above the minimum size of capture regulated by fishery management agencies (i.e., most fish were small and marginally legal). Nine of 13 grouper species, nine of nine snapper species, and six of seven grunt species for which there were data are below the 30% SPR, meaning that these species are



Population dynamics and fishery sustainability metrics for black grouper, a heavily overfished species at three levels (red dots) of fishing mortality. Heavy fishing pressure reduces the average size of individuals in the population over time, making the stock younger and successively eliminating older, more fecund size classes. Fecundity (i.e., number of eggs produced) increases exponentially with the size of fish. Protection of large fish is required to sustain fishery yields and maintain or improve fish spawning stock biomass.



Estimates of percent Spawning Potential Ratio (% SPR) for 29 species of Florida Keys reef fishes, comprising of groupers, snappers, and grunts. Red bars show species that are overfished (i.e., below 30% SPR). Open bars indicate stock that are not overfished.

overfished. Overall, 63% of the 29 stocks that could be analyzed were overfished. The Florida Keys reef fishery exhibits classic "serial overfishing" in which the largest, most desirable, and vulnerable species are exploited in the following order: exploitation is highest for groupers, followed by snappers, followed by grunts. Generally, the most valuable groupers and snappers currently have the lowest spawning potential.

Several factors led to the establishment of the Sanctuary and associated Marine Protected Areas, including concerns about the rapid growth in the human population in south Florida, habitat destruction, and declining water quality. Reversing adverse trends in the reef fishery in south Florida and the Florida Keys requires innovative approaches for controlling exploitation rates. The coupling of traditional management practices, such as fish size and capture limits, with a spatial network of adequately sized and strategically located no-take marine reserves may provide an ecosystem management strategy for achieving long-term goals of protecting biodiversity while maintaining sustainable fisheries. An important component required for the success of this effort is a conscientious, continuous assessment program for integrating fishery-independent and fishery-dependent data to evaluate the effectiveness of marine reserves. With adaptive management, improvements to fish stocks can be obtained over time.

Fishing patterns have changed over time

Loren E. McClenachan

Fishing has always been an important part of the culture and economy of south Florida and the Florida Keys. As early as the 18th century, the coast of Florida was "covered with fishermen's huts." Overfishing during the last century has reduced populations of once abundant fish, invertebrates, and reptiles in the Florida Keys. For example, green turtles, which historically nested and fed throughout the Keys, are rare today. Many fish are overexploited, and several fish that were commonly caught in the 18th and 19th centuries, such as sawfish, are listed by the International Union for Conservation of Nature as Critically Endangered or Endangered.

19th century

In the second half of the 19th century, new export fisheries were developed in the Keys. By the 1840s, more than 100 boatloads of fish were sent annually to Havana, Cuba, where the fish market was known for its variety and quantity of fresh fish. The Key West Green Turtle Cannery opened in 1849, and marine sponges were first exported in the same year. By 1890, turtles and sponges were the two major marine exports sent to northern markets, and populations of both had precipitously declined.

C. H. Anderson courtesy of D. Gallager

Historically, sharks were harvested commercially for their skins and oil. The average length of sharks found in the Florida Keys has declined by more than 50% in the past 50 years.

Shifting baselines

The debate about the status of fisheries in the Florida Keys is a classic example of the "shifting baselines syndrome." It has been mistakenly assumed that the abundance and sizes of fishes seen in the 1980s represented pristine conditions. However, most prized fishes had been reduced to a small fraction of their pristine abundance long before.

20th century

In the 20th century, both commercial and recreational fisheries grew in Florida. Sharks were harvested commercially in the 1920s – 1940s for their skins, which were turned into leather, and later for vitamin D, which was extracted from their liver oil. After World War II, the Keys became a major recreational fishing destination, and the infrastructure supporting recreational fisheries in the Keys increased rapidly. The landings of several commercial fisheries peaked in the 1970s – 1980s, and now many present-day fish stocks are considered to be overfished.

Back to the future

Fishing is not what it used to be, but the prospects for recovery are promising. Abundances of several fish species have increased within no-take marine reserves in the Florida Keys National Marine Sanctuary, providing hope for the future of fishing in the Keys.

Wil-Art Studio, courtesy of Monroe County Public Library

Wil-Art Studio, courtesy of Monroe County Public Library

L.E. McClenachan - SFU

An example of a day's catch in 1957 (top), the 1980s (middle), and in 2007 (bottom).

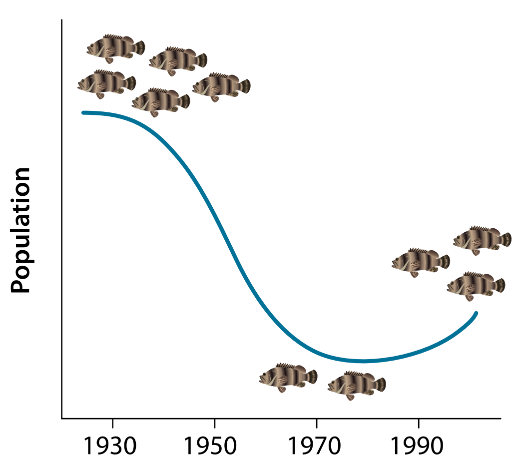
Shifting baselines alter the public perception of the environment

Dalal Al-Abdulrazzak

The concept of what is pristine in the oceans often is limited to the collective memory of observers. As each generation redefines according to personal experience what was "natural" in the oceans, degraded states can become accepted as normal. This loss of the perception of change is known as a "shifting baseline." The term was first used by fisheries scientist Dr. Daniel Pauly in reference to fisheries management in which scientists failed to correct baseline population size and, thus, worked from a shifted baseline. Scientists determine baseline conditions as reference points from which to evaluate changes in the health of populations, communities, and ecosystems. If the original baseline condition for a degraded ecosystem is known, measures can be taken to help restore the ecosystem to that target condition.

The lack of knowledge on baseline conditions of pristine marine ecosystems is especially a problem for coral reefs, which are both the most diverse marine ecosystem and the most threatened. Most of the tropical coastal oceans worldwide are so degraded that many pristine reefs have essentially disappeared. Because detailed study of coral reefs did not begin until the invention of SCUBA diving in the 1940s, most of our knowledge has been focused on coral reefs that were already moderately to severely degraded. Paleoecologists, geologists, and historical geologists attempt to characterize past conditions by studying biophysical conditions and historical evidence to describe changes to the environment and establish more accurate baselines.

Photographs of the same coral head at Grecian Rocks (Key Largo) in 1959, 1988, and 1998. A visitor to the reef in 1998 or later, who has never seen a coral reef before, may conclude that the reef is alive and healthy, even though present-day condition is not what a healthy, pristine coral reef actually looks like.



The biomass and population numbers of goliath groupers in south Florida have increased by more than 30% since the 1990s. Although it may seem like the population is recovering, a closer look at historical records indicates that goliath populations have been declining since at least the 1950s. The numbers from the 1990s represent a baseline that has shifted.

You can help to lessen impacts to the environment

William L. Kruczynski and Pamela J. Fletcher

The natural resources of planet Earth are finite and must be conserved for future generations. Do all that you can to leave a small human "footprint."

- Become educated about global warming and sea-level rise. Recognizing the reality of the problem is the first step.
- Encourage public officials to establish policies and programs that are good for the environment.
- Support the use of solar power and other alternatives to fossil fuels for production of energy.
- Reduce, reuse, recycle. Choose reusable products instead of disposables, such as single-use plastic water bottles.
- Buy products with minimal packaging. Recycling half of your household waste can save 1089 kilograms (2400 pounds) of carbon dioxide annually.
- Use less heat and air conditioning. Setting your thermostat 2°F (lower in winter and higher in summer) can save about 907 kg (2000 lbs) of carbon dioxide per household annually.
- Drive less and drive smart. Bicycle, walk, and use carpools when possible. Buy energy-efficient vehicles.
- Buy energy-efficient products and appliances. If every U.S. family replaced one regular bulb with a fluorescent bulb, it would eliminate 41 million metric tons (45 million tons) of greenhouse gases.
- Use less hot water. Washing clothes in warm or cold water can save more than 227 kg (500 lbs) of carbon dioxide per household annually.
- Hang clothes outside to dry instead of using a clothes dryer. Use a clothesline in your attic, garage, or basement during inclement weather.
- Turn off the lights when they are not needed. Turn off water when you are not using it.
- Plant a tree. A single long-lived tree will absorb over a ton of carbon dioxide during its lifetime.
- Landscape with native plants and water sparingly. Use drip irrigation if necessary. Mulched plants require less water.
- Plant a vegetable garden. Use containers if space is limited.
- Reduce use of pesticides, herbicides, and other toxic chemicals and do not apply near water.
- Use reusable bags when shopping for groceries or other items.
- Buy products from sustainable fisheries, including pond-reared fisheries products.
- Obey fishing and hunting regulations.

L. Perez - NPS

A single long-lived tree will absorb over a ton of carbon dioxide during its lifetime. Use native trees for landscaping to reduce water consumption and use of fertilizers.

Introduction citations

1. CLM Search. 2010. United States Real Estate and Demographics. Available from: http://www.clrsearch.com/Demographics/FL/South_Florida/Population_Growth_Statistics/Growth%20statistics,%20Broward%20County. (Cited 23 Jan 2011). *Growth statistics, Broward County.*
2. Wikipedia. 2011. South Florida Metropolitan Area. Available from: http://en.wikipedia.org/wiki/South_Florida_metropolitan_area (Updated 22 Jan 2011; cited 23 Jan 2011). *South Florida demographics.*
3. South Florida Regional Planning Council. 2010. South Florida Region Resident Population Estimates and Projections 1920-2030. Available from: http://www.sfrpc.com/Dick%27s%20Demographics/PopProj_SF3.pdf (Updated 03 Oct 2010; cited 23 Jan 2011). *South Florida population growth and projections.*
4. Broward County Florida Office of Urban Planning and Redevelopment. 2004. Broward-by-the Numbers. Available from: http://www.broward.org/PlanningAndRedevelopment/DemographicsAndEconomics/Documents/bbtn20.pdf (Updated Mar 2004; cited 23 Jan 2011). *Projected population growth in south Florida.*
5. Aramson A. 2010. Study predicts population growth resumes for southeast Florida. The Palm Beach Post, 3 Mar. 2010. Available from: http://www.palmbeachpost.com/news/study-predicts-population-growth-resuming-for-southeast-florida-310740.html (Cited 23 Jan 2011). *Projected population growth continues in south Florida.*
6. Muenker R. 2008. Everglades National Park, USA: Gators, crocs and birds galore populate unique National Park. One World Heritage. Available from: http://www.muenkermedia.com/owh/site-Everglades.shtml (Updated Nov 2008; cited 23 Jan 2011). *Everglades declared a UNESCO World Heritage site.*
7. Arms K. 2000. Environmental Science. Austin: Holt, Rinehart and Winston. Chapter 7. Aquatic Ecosystems, Section 1–Freshwater Ecosystems. Available from: http://www.nexuslearning.net/books/Holt_Env_Science/7-1.pdf (Cited 26 Mar 2012). *The importance and threats to freshwater wetlands.*
8. Fourqurean JW, Durako MJ, Hall MO, Hefty LN. 2002. Seagrass distribution in south Florida: a multiagency coordinated monitoring program. In: Porter JW, Porter KG (eds.). The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook. Boca Raton, FL: CRC Press. p 497-522. *Seagrasses are a dominant component of the hydroscape of south Florida.*
9. Viele J. 1996. The Florida Keys, A History of the Pioneers. Sarasota: Pineapple Press, 154 p. *A history of settlement of the Florida Keys.*
10. Florida International UniversityArchival Library and Museum. South Florida's Natural History, 1884 to 1934. Available from: http://www2.fiu.edu/~glades/reclaim/timeline/index.htm (Cited 23 Jan 2011). *A timeline of the history of south Florida and the Everglades.*
11. Shelton WR. 1957. Land of the Everglades, Tropical Southern Florida. Florida Department of Agriculture, 44 pp. *The uniqueness of tropical south Florida.*
12. Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL, Robbins LL. 2006. Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research. Report of a workshop held 18–20 April 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey, 88 p. *Thorough analysis of the history of effects of increased carbon dioxide on calcification of marine organisms and research recommendations that should be pursued over the next 5 to 10 years.*
13. Hendriks IE, Duarte CM, Álvarez M. 2010. Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. Estuar Coast Shelf Sci. 86:157-164. *Some marine biota may be less sensitive to lowering of ocean pH than previously predicted.*

Further reading

Atkinson MJ, Cuet P. 2008. Possible effects of ocean acidification on coral reef biogeochemistry: topics for research. Mar Ecol Prog Ser. 373:249-256. *Review of recent literature on how ocean acidification may influence coral reef organisms and coral reef communities. Authors state that it is unclear as to how, and to what extent, ocean acidification will influence calcium carbonate calcification and dissolution, and affect changes in community structure of present-day coral reefs.*

Ault JS, Bohnsack JA, Meester GA. 1998. A retrospective (1979-1996) multi-species assessment of coral reef fish stocks in the Florida Keys. Fish Bull. 96:395-414. *Overfishing has likely altered the structure and dynamics of the Florida Keys reef fish community.*

Carson R. 1955. The Edge of the Sea. Boston:Houghton Mifflin, 276p. *A classic summary of the natural history of the sea.*

Done TJ. 1991. Effects of tropical cyclone waves on ecological and geomorphological structures on the Great Barrier Reef. Cont Shelf Res. 12:859-872. *Local wind-generated waves, not ocean swells, may be the major cause of destruction to coral reefs during major storm events.*

Engle VD, Summers JK. 2000. Biogeography of benthic macroinvertebrates in estuaries along the Gulf of Mexico and western Atlantic coasts. Hydrobiologia 436:17-33. *Boundaries of biogeographic provinces are proposed based upon community composition of benthic macroinvertebrates from 870 estuarine sites.*

Fong P, Lirman D. 2008. Hurricanes cause population expansion of the branching coral *Acropora palmata* (Scleractinia): Wound healing and growth patterns of asexual recruits. Mar Ecol. 16:317-335. *Wound healing, rate of asexual recruitment, and growth rate of elkhorn corals were impacted by Hurricane Andrew.*

Gallager D. (ed.) 1997. The Florida Keys Environmental Story, Big Pine Key, FL: Sea Camp Assoc. Inc., 371 p. *Summary of Monroe County's natural environment and cultural heritage.*

Gibson T, Wanless H, Klaus J, Foster-Turley P, Florini K, Olson T. 2008. Corals and Climate Change: Florida's National Treasures at Risk. Environmental Defense Fund, 40 p. *Thorough summary of the state of the knowledge on the effects of increasing greenhouse gases on global warming, coral bleaching, and ocean acidification.*

Griffin DW, Kellogg CA, Shinn EA. 2001. Dust in the wind: long-range transport of dust in the atmosphere and its implications for global and ecosystem health. Global Change and Human Health 2:2-15. *Summary of origins and consequences of dust from Africa riding winds across the Atlantic Ocean.*

Griffin DW, Garrison VH, Herman R, Shinn EA. 2001. African desert dust in the Caribbean atmosphere: microbiology and public health. Aerobiologia 17:203-213. *Hundreds of millions of tons of dust transported annually from Africa and Asia to the Americas may be adversely affecting coral reefs and other downwind ecosystems. Viable microorganisms, macro- and micronutrients, trace metals, and an array of organic contaminants carried in the dust air masses and deposited in the oceans and on land may play important roles in the complex changes occurring on coral reefs worldwide.*

Jackson JBC, Kirby MX, Berger WH, Bjorndal KA, Bostford LW, Bourque BJ, Bradbury RH, Cooke R, Erlandson J, Estes J, et. al. 2001. *Historical overfishing and the recent collapse of coastal ecosystems. Science 293:629-637. Plenary article on the history of overfishing and the collapse of coastal fisheries.*

Knowlton N, Jackson JBC. 2008. Shifting baselines, local impacts, and global change on coral reefs. PLoS Biology 6:215-220. *Shifting baseline theory is explained in detail.*

Langdon C , Atkinson MJ. 2005. Effect of elevated CO2 on photosynthesis and calcification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. J Geophys Res. 110 (C09S07). *Ocean acidification resulting from human emissions of carbon dioxide has already lowered and will further lower surface ocean pH. Mussel and oyster calcification may decrease by 25 and 10%, respectively, by the end of the century, at rates of carbon dioxide increases given in the IPCC scenario.*

Lodge TE. 2010. The Everglades Handbook: Understanding the Ecosystem, 3rd edition. Boca Raton: CRC Press, 392 p. *A comprehensive treatise on the ecology of the Everglades.* Marshall FE, Wingard GL, Pitts PA., 2009, A simulation of historic hydrology and salinity in Everglades National Park: Coupling paleoecologic assemblage data with regression models. Estuar Coast 32(1):37-53. *A statistical method for linking statistical models with paleoecologic data to estimate historic flow and stage in the Everglades wetlands and salinity in the estuaries.*

Massel SR, Done TJ. 1993. Effects of cyclone waves on massive coral assemblages on the Great Barrier Reef: meteorology, hydrodynamics and demography. Coral Reefs 12:153-166. *Cyclonic waves affect density, structure, and local distribution of coral assemblages by acting as agents of mortality and colony transport.*

McPherson BF, Halley R. 1996. The South Florida environment—a region under stress. U. S. Geological Survey, Circular 1134. Washington, DC: United States Government Printing Office. *A summary of the natural environment of south Florida (the landforms, climate, geology and hydrology), the history of the alterations to the environment through development, agriculture, urbanization, and water control, and the environmental stresses caused by the interaction of these natural and human factors.*

Mendolsohn R, Neumann J. (eds.) 1999. The Impact of Climate Change on the United States Economy. Cambridge: Cambridge University Press, 344 pp. *Choices made in the next few decades to either reduce emissions of greenhouse gases or continue at the current pace of emission growth will have large and widespread ramifications on the U.S. economy.*

Mumby PJ, Edwards AJ, Arias-Gonzalez JE, Lindeman KC, Blackwell PG, Gall A, Gorczynski MI, Harbone AR, Pescod CL, Renken H, Wabnitz CCC, Llewellyn G. 2003. Mangroves enhance the biomass of coral reef fish communities in the Caribbean. Nature 427: 533-536. *Global loss of mangroves exceeds 35%. They provide an intermediate nursery habitat that may increase the survivorship of young fish. Mangroves in the Caribbean strongly influence the community structure of fish on neighboring coral reefs.*

Myers RL, Ewel JJ (eds). 1990. Ecosystems of Florida. Orlando, FL:Univ. of Central Florida Press, 765 p. *A comprehensive and authoritative account of the state's natural resources by habitat type, including management priorities.*

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres Jr. F. 1998. Fishing down marine food webs. Science 279: 860-863. *Discussion on how fishermen fish out one species and move on to another, each getting smaller and farther down the food chain.*

Pauly D, Palomares ML. 2005. Fishing down the marine food web: it is far more pervasive than we thought. Bull Mar Sci. 76: 197-211. *Discussion about how fishermen have moved from large species to smaller species and that most fisheries of the world are not sustainable.*

Perry DD, Cahill TA, Eldred RA, Dutcher DD. 1997, Long-range transport of North African dust to the eastern United States. J Geophys Res. 102:11,225-11,238. *African dust collected in the Rocky Mountains and other remote areas.*

Pimm SL, Davis GE. 1994. Hurricane Andrew. Bioscience 44:224-229. *Analysis of the impacts of Hurricane Andrew on the biotic environments of south Florida.*

Rahmstorf S. 2007. A Semi-empirical approach to projecting future sea-level rise. Science 315 (5810):368-370. *The rate of sea-level rise is roughly proportional to the magnitude of warming above the temperatures of the Pre-Industrial Age.*

Rogers CS, Beets J. 2001. Degradation of marine ecosystems and decline of fishery resources in marine protected areas in the U.S. Virgin Islands. Environ Conserv. 28:312-322. *Living coral cover has decreased and macroalgae cover has increased in two marine protected areas. Damage from boats, hurricanes, and coral diseases are causing deterioration in the marine protected areas.*

Ross MS, O'Brien JJ, Da Silveira Lobo Sternberg L. 1994. Sea-level rise and the reduction of pine forests in the Florida Keys. Ecol Appl. 4:144-156. *Salinization of ground and soil water that occurs with rising sea level resulted in the death of pine trees. Further rises in sea level will result in the replacement of species-rich upland communities with mangroves.*

Serafy JE, Ault JS, Capo TR, Schultz DR. 1999. Red drum, *Sciaenops ocellatus* L., stock enhancements in Biscayne Bay, FL, USA: Assessment of releasing unmarked early juveniles. Aquacult Res. 30:737-750. *Assessment of fisheries in Biscayne Bay.*

Serafy JE, Lindeman KC, Hopkins TE, Ault JS. 1997. Effects of freshwater canal discharges on fish assemblages in a subtropical bay: field and laboratory observations. Mar Ecol Progr Ser. 160:162-172. *Redfish have not been seen in Biscayne Bay since the drainage canal system was put in place and altered the salinity regime of the Bay.*

Sheppard C. 1995. The shifting baseline syndrome. Mar Pollut Bull. 30:766-767. *Different generations accept the present state of the environment as the norm.*

Shinn EA, Smith GW, Prospero JM, Betzer P , Hayes ML, Garrison V, Barber RT. 2000. African dust and the demise of Caribbean coral reefs. Geophys Res Lett. 27:3029-3032. *Decline in Caribbean coral reefs is coincidental with large increases in transatlantic dust transport.*

Smith III TJ, Robblee MB, Wanless H, Doyle TW. 1994. Mangroves, hurricanes, and lightning strikes. Bioscience 43:256-262. *Assessment of environmental damage to natural resources of Everglades and Biscayne National Parks after the passage of Hurricane Andrew (1992).*

Tilmant JT, Curry RW, Jones R, Szmant A, Zieman JC, Flora M, Robblee MB, Snow RW, Wanless H. 1994. Hurricane Andrew's effects on marine resources. Bioscience 43:230-237. *Assessment of the effects of Hurricane Andrew (1992) on marine resources of south Florida.*

Willard DA, Cronin TM. 2007. Paleoecology and ecosystem restoration: Case studies from Chesapeake Bay and the Florida Everglades: Front Ecol Environ. 5(9):491-498. *A non-technical summary of how paleoecologic data can be used by restoration managers to understand patterns of change on decadal and longer time frames and why this information is critical to successful restoration.*

Website references

Casey B. 2006. Bacteria and fungi ride dust across oceans. Live Science. Available from: http://www.livescience.com/environment/060605_disease_dust.html (Accessed 24 Jan 2011). *Dust clouds blowing across the Atlantic Ocean carry pathogens that might reach the United States. Dust comes from the Sahara Desert and the dust season runs from May to October.*

Cowardin LM, Carter V, Golet FC, LaRoe ET. 1979. Classification of wetlands and deepwater habitats of the United States. U. S. Department of the Interior, Fish and Wildlife Service, Washington, D.C. Jamestown, ND: Northern Prairie Wildlife Research Center Home Page. Available from: http://www.npwrc.usgs.gov/resource/1998/classwet/classwet.htm (Accessed 23 Jan 2011). *Description and distribution of the 10 marine and estuarine provinces in North America.*

Elfers SC. 1988. Element Stewardship Abstract for *Casurina equisetifolia*. The Nature Conservancy. Available from: http://www.invasive.org/gist/esadocs/documnts/casuequ.pdf (Accessed 24 Jan 2011). *Description, biology, natural history, and management of Australian pine. Description of spread in distribution following Hurricane Donna.*

Enchanted Learning. 1997-2010. Geologic Time Scale. Available from: http://enchantedlearning.com/subjects/Geologictime.html (Accessed 5 Jul 2011). *Table of geologic time showing pivotal events.*

Encyclopedia Britanica Online. 2011. Fossil record: Geologic time scale with major evolutionary events. Available from: http://www.britannica.com/EBchecked/topic-art/197367/1650/The-geologic-time-scale-from-650-million-years-ago-to (Updated 24 Jan 2011; accessed 24 Jan 2011). *Encyclopedia Britannica's chart of Eras, Periods, and main evolutionary events.*

Fenner D. 2011. The loss of large fish on coral reefs. Shark Savers. Available from: http://www.sharksavers.org/en/education/sharks-are-in-trouble/399-loss-of-large-fish-on-coral-reefs.html (Accessed 24 Jan 2011). *As reefs degrade, each generation uses a lower condition as the baseline to judge further losses. This is called the "shifting baseline syndrome."*

Florida International University Libraries, Digital Collection Center. 2005-2010. Everglades Digital Library. Available from: http://cwis.fcla.edu/edl/ (Accessed 24 Jan 2011). *Historical photographs and information about the Everglades.*

Halley RB, Vacher HL, Shinn EA. 1997. Geology and hydrogeology of the Florida Keys. In: Vacher HL, Quinn T (eds.). Geology and Hydrology of Carbonate Islands. Developments in Sedimentology 54. Amsterdam: Elsevier Science. p. 217-248. Available from: http://sofia.usgs.gov/publications/papers/keys_geohydro/hydrogeology.html (Accessed 23 Jan 2011). *Analysis of the formation and geological history of the Florida Keys.*

Hurricanecity.com. Hurricane Andrew Aug 24 1992. Available from: http://www.hurricanecity.com/andrew.htm (Accessed 24 Jan 2011). *Statistics from the aftermath of the second most costly natural disaster in U.S. history.*

Intergovernmental Panel on Climate Change. 2007. Climate Change Synthesis Report: Summary for Policy Makers. Available from: http://www.ipcc.ch/pdf/assessment-report/ar4/syr/ar4_syr_spm.pdf (Updated Nov 2007; accessed 23 Jan 2011). *Warming of the climate system is unequivocal, as is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice, and rising global average sea level.*

International Commission on Stratigraphy. 2010. Time Scale Chart. Available from: http://www.stratigraphy.org/column.php?id=Chart/Time Scale (Updated Sep 2010; accessed 26 Mar 2012). *Geologic time scale chart.*

Lane E. (ed.) 1994. Florida's Geological History and Geological Resources. Florida Geological Survey, Serial Publication 35, 36 p. Available from: http://purl.fcla.edu/fcla/dl/UF00000124.pdf (Accessed 24 Jan 2011). *A detailed review of the geological history of the Florida peninsula.*

Lidz, BH. 2005. Setting: Climatic and oceanographic setting. USGS South Florida Information Access. Available from: http://SOFIA.USGS.gov/publications/papers/keys_geohydro/setting.html (Updated 21 Jan 2005; accessed 5 Jul 2011). *A summary of the Pleistocene geology of the Florida Keys.*

National Earth Science Teachers Association. 2010. Geologic Time: Our Earth is Old! Windows to the Universe. Available from: http://www.windows.ucar.edu/tour/link=/earth/geology/hist_geotime.html (Updated 20 Aug 2004; accessed 24 Jan 2011). *Image of geological time scale.*

National Park Service. 2007. Lessons from Everglades National Park, USA. Operational Guidelines on Benchmarks and Chapter IV Operational Guidelines. World Heritage Committee, Paris, France, April 2007. Available from: whc.unesco.org/uploads/events/documents/event-396-3.ppt (Accessed 24 Jan 2011). *Importance of the Everglades and restoration activities.*

National Weather Center. 2010. Florida hurricane info, tips, maps, safety preparations. Available from: http://www.floridahurricane.net/ (Accessed 24 Jan 2011). *Hurricane strike statistics.*

NOAA Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division. 2010. Frequently Asked Questions. Available from: http://www.aoml.noaa.gov/hrd/tcfaq/tcfaqHED.html (Accessed 23 Jan 2011). *Frequently Asked Questions on tropical cyclones.*

Pilkey O, Young R. 2009. The Rising Sea. Washington, DC: Island Press. 224 p. *A summary on how rising sea levels will affect coastal communities.*

Rahmstorf S. 2010. A new view on sea-level rise. Nature Reports Climate Change, v. 4, p. 44-45. Available from: http://www.nature.com/reports/climatechange (Accessed 11 March 2011). *The Intergovernmental Panel on Climate Change may have underestimated the risk of sea-level rise by assuming zero contribution of Greenland and Antarctic ice sheets.*

Salenger A. Hurricane impacts on the coastal environment. USGS Marine and Coastal Geology Program. Available from: http://marine.usgs.gov/fact-sheets/hurricane/hurricane-txt.html (Accessed 24 Jan 2011). *Summary of damage to coastal environment by hurricanes.*

Schmidt LJ. 2001. When the dust settles. NASA Earth Observatory. Available from: http://earthobservatory.nasa.gov/Features/Dust/ (Updated 24 Jan 2011; accessed 24 Jan 2011). *African dust can help or hinder coral reefs in the Caribbean.*

Schrope M. 2008. Sleeping with the fishes. Nature Reports- Climate Change. Available from: http://www.nature.com/climate/2008/0812/full/climate.2008.127.html (Accessed 24 Jan 2011). *Ocean acidification is the latest in a slew of threats to coral reefs.*

Science Daily. 2009. Historical photographs expose decline in Florida's reef fish, study finds. Reprinted from material provided by University of California, San Diego, March 2, 2009. Available from: http://www.sciencedaily.com releases/2009/02/090217141813.htm (Accessed 24 Jan 2011). *Archival photographs spanning more than five decades were analyzed and calculate a drastic decline of so-called "trophy fish" caught around coral reefs surrounding Key West, Florida.*

Scripps Institution of Oceanography. 2009. Historical photographs expose decline in Florida's reef fish, study finds. Scripps News, 17 Feb 2009. Available from: http://scrippsnews.ucsd.edu/

Releases/?releaseID=959 (Accessed 24 Jan 2011). *Study concludes that there was an 88% decline in the estimated weight of large predatory fish between the 1950s and present.*

South Florida Sun Sentinel. 2011. The 11 Worst Hurricanes. Available at: http://www.sun-sentinel.com/news/local/southflorida/sfl-aug2001hurricanehisto ry,0,637516.storygallery (Accessed 24 Jan 2011). *The 11 worst hurricanes in south Florida history.*

Sparling B. 2001. Ozone depletion, history and politics. NAS Educational Resources. Available from: http://www.nas.nasa.gov/About/Education/Ozone/history.html (Updated 30 May 2001; accessed 24 Jan 2011). *History of the use of chlorofluorocarbons and their impacts on the ozone layer.*

United States Geological Survey. 2009. This Dynamic Earth: The story of plate tectonics. Available from: http://pubs.usgs.gov/gip/dynamic/dynamic.html (Updated 13 Jan 2009; accessed 07 Jul 2011). *Fragmentation of the supercontinent Pangaea.*

United States Geological Survey. 2010. Ecosystem History of South Florida Estuaries Data. South Florida Information Access- Data Exchange. Available from: http://sofia.usgs.gov/exchange/flaecohist/ (Updated 10 Jan 2011; Accessed 24 Jan 2011). *Data from paleoecologic studies of the estuaries from the cores and modern samples used to interpret the cores. Also contains links to online publications and reports on the ecosystem history of south Florida's estuaries.*

United States Geological Survey. South Florida Information Access, Integrated Science. Available from: http://sofia.usgs.gov/ (Updated 13 Jan. 2011; accessed 24 Jan 2011). *South Florida Information Access website, provides reports, data, publications and links to over 50 projects relevant to the South Florida ecosystem restoration effort.*

United States Geological Survey, St. Petersburg Coastal and Marine Science Center. 2010. The effects of African dust on coral reefs and human health. Available from: http://coastal.er.usgs.gov/african_dust (Updated 14 Jun 2010; accessed 24 Jan 2011). *Chemical contaminants (pesticides, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and metals) and microorganisms have been identified in dust air samples.*

West L. 2011. Top 10 things you can do to reduce global warming. About.com-Environmental Issues. Available from: http://environment.about.com/od/globalwarming/tp/globalwarmtips.htm (Accessed 24 Jan 2011). *Suggestions to reduce global warming.*

Wikipedia. Tropical cyclone. Available from: http://en.wikipedia.org/wiki/Hurricane (Updated 11 Jan 2011; accessed 24 Jan 2011). *Summary of factors affecting the formation and distribution of tropical cyclones.*

Wilkinson J. General History of Hurricanes- Hurricane Statistics. Keys Historeum, Historical Preservation Society of the Upper Keys. Available from: http://www.keyshistory.org/35-hurr-statistics.html (Accessed 24 Jan 2011). *A summary of Florida hurricanes, 1900-2000.*

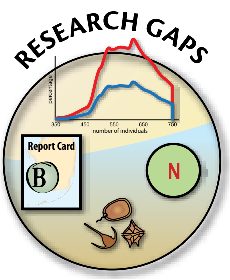
Wingard GL. 2004. Changing salinity patterns in Biscayne Bay, Florida. USGS Fact Sheet 2004-3108. Available from: http://pubs.usgs.gov/fs/2004/3108/fs2004-3108.html (Updated 01 Mar 2005; accessed 24 Jan 2011). *Paleoecological study reveals changes in historical salinity patterns in Biscayne Bay, Florida with implications for management.*

Wingard GL, Hudley JW, Marshall FE. 2010. Estuaries Of The Greater Everglades Ecosystem: Laboratories of Long-term Change. USGS Fact Sheet 2010-3047. Available from: http://pubs.usgs.gov/fs/2010/3047/index.html (Updated 01 Jul 2010; accessed 06 Jul 2011). *Paleoecologic investigations provide quantitative data on historic variability of salinity that can be used in statistical models to estimate historical freshwater flows.*

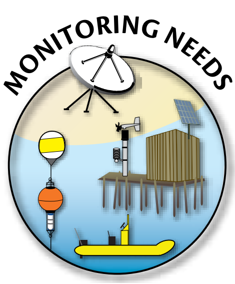
2. OCEANOGRAPHIC CONNECTIVITY

Oceanographic Connectivity Chapter Recommendations

- Recognize the importance of **communication and cooperation** across political boundaries to effectively manage a large, hydrologically open system.
- Acknowledge **regional and global threats** when developing management plans to address local actions.
- Practice **adaptive management** to improve decision making using the best available science.



- Continue to update, develop, and test **hydrographic models** to predict influences of farfield sources of pollution on ecological processes.
- Assess **effects of restricted movement of water** from the Gulf of Mexico and Florida Bay to the Atlantic Ocean in areas with restricted flows.



- Continue to collect long-term data of current speed and direction, water temperature, salinity, and other **water quality** parameters that are required to validate and update oceanographic models.
- Incorporate **remote sensing** where applicable to gather synoptic data over large geographic areas.
- Quantify the frequency and length of **upwelling events** to allow the development of more accurate nutrient loading models to coral reef habitats.
- Maintain or increase the number of Sustained Ecological Research Related to Management of the Florida Keys Seascape Coastal-Marine Automated Network (**SEAKEYS C-MAN**) stations to provide cost effective real-time oceanographic and meteorological data.

Chapter title page: The Caribbean Sea, Gulf of Mexico, and Atlantic Ocean are hydrologically connected. Google Earth.

Introduction

Oceanography is a multifaceted branch of science that studies the ocean. Because 71% of the Earth is covered in seawater, it is essential to understand worldwide oceanic interactions across the air-sea interface. The atmosphere and ocean are linked because of evaporation, precipitation, and exchange and absorption of gases as well as thermal flux and solar insolation. The effects of these factors occur at varying geographic scales.

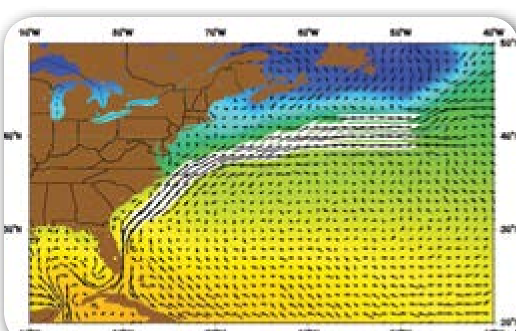
South Florida is an area of complex oceanographic patterns because it is located at the confluence of the Atlantic Ocean and Gulf of Mexico, which results in dynamic tidal and surface current patterns. The Gulf Stream system sweeps past south Florida as the Florida Current and connects the area to upstream sources in the Caribbean Sea and Gulf of Mexico. Larval, juvenile, and adult forms of marine life "ride" the Gulf Stream currents, are delivered to south Florida, and help to maintain the diverse and abundant sea life in Florida.[1] Pollutants can also be entrained in the currents and may be delivered far downstream from their sources. For example, pesticides and fertilizers used on corn fields in the Midwest of the United States can be carried downstream by the Mississippi River, entrained in the Loop Current, and delivered to south Florida.

The south Florida coastal region comprises oceanographic subregions defined by their physical characteristics, flow properties, and species composition. The oceanographic linkage between the subregions depends on the degree of transport and interaction of currents connecting the subregions as well as on connections over the whole coastal region provided by the surrounding Gulf Stream currents and eddies. Periodic tropical storms and hurricanes can strongly influence salinity, water quality, and the circulation of water within and among the subregions, as can oceanic forcing functions such as deep ocean upwelling and freshwater pulses from terrestrial sources.[2]

The south Florida marine environment is the receiving body of water for the Greater Everglades Ecosystem, including but not limited to the Kissimmee River, Lake Okeechobee, St. Lucie River, Shark River, Taylor Slough, and the Caloosahatchee. Historically, freshwater flowed unimpeded through the system into Biscayne Bay and Florida

Oceanography

Major divisions of oceanography include: geological oceanography, the study of the structure, formation, and movement of the ocean floor; physical oceanography, the study of physical attributes of ocean water, such as waves, tides, currents, salinity, and temperature; chemical oceanography, the study of the chemistry of ocean water; biological oceanography, the study of the animals and plants that live in the sea; and meteorology, the study of the interactions between the atmosphere and the ocean. Oceanographers may specialize in one or more disciplines or blend several disciplines to further the understanding of the oceans, their inhabitants, and biophysical and biochemical processes.



From Gyory, Mariano, and Ryan (2001-2008)

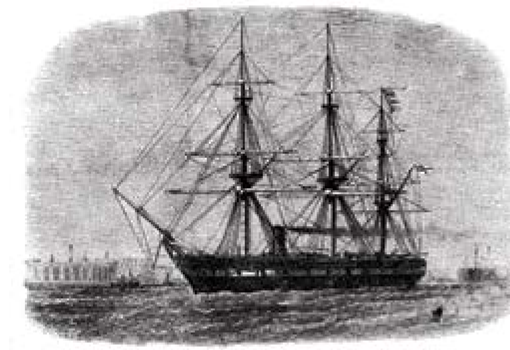
A computer model of the Gulf Stream current system represented by the Mariano Global Surface Velocity Analysis. The Gulf Stream transports a significant amount of warm water poleward. Water from the Caribbean Sea is funneled into the Gulf of Mexico, past the Yucatán Peninsula, and forms the Loop Current in the Gulf. The Loop Current becomes the Florida Current as the water sweeps through the Florida Straits.

Bay. Hydrologic modifications to the watershed have affected the quantity, quality, timing, and distribution of freshwater to downstream areas and have shunted much of the freshwater drainage to the sea via the Caloosahatchee (Gulf side) and St. Lucie Canal (Atlantic side). As a result, salinity and other water chemistry parameters have been altered in downstream areas.

Seasonal changes in rain (wet and dry season patterns) and wind direction and speed further add to the oceanographic complexity of the area. Wind direction and speed are major drivers of ocean currents. Strong and persistent southeasterly winds can raise water levels on the Atlantic side of the Florida Keys, resulting in nontidal current reversals toward the Gulf side of the Keys. Wind forcing is especially important in the shallow waters of Florida Bay, providing the connecting link between inflow from the Gulf and outflow to the Atlantic and vice versa. Causeways constructed in the Florida Keys for Flagler's Railroad disrupted the normal exchange of surface waters between Atlantic and Gulf sides of the Keys and affected salinity patterns and flushing times in Florida Bay.[3]

A historical perspective of oceanographic science and research in south Florida

Humankind has been interested in the oceans since prehistoric times. Early exploration of the oceans was primarily for map making and describing the creatures that fishermen sighted or brought up in their nets.[4] Modern oceanography began as a field of science less than 130 years ago, in the late 19th century, when Americans, British, and other Europeans launched expeditions to explore ocean currents, ocean life, and the seafloor adjacent to their coastlines. The first scientific expedition to explore the oceans and seafloor was the Challenger Expedition. From 1872 – 1876, Charles Wyville Thompson and Sir John Murray led the research cruise onboard the British three-masted warship HMS *Challenger*. The results of that hallmark voyage were published in 50 volumes covering biological, physical, and geological oceanographic findings, and approximately 4700 species of new flora and fauna were described. The Challenger Expedition established oceanography as a quantifiable science.[5]



NOAA

HMS *Challenger*, a British Navy corvette (small warship), was converted into an oceanographic ship with laboratories and scientific equipment. The Challenger Expedition (1872 – 1876) was the first worldwide study of the oceans and seafloor.

The first ship built specifically for oceanographic purposes was the *Albatross* in 1882. Its 4-month voyage in 1910 in the North Atlantic Ocean, headed by Sir John Murray and Johan Hjort, was the most ambitious oceanographic and marine zoological project undertaken at that time.[6]

At the end of the 19th century and the beginning of the 20th century, several notable oceanographic institutes were founded in the United States, including the Scripps Institution of Oceanography (1892) and Woods Hole Oceanographic Institution (1930). The first acoustic measurements of the depth of the seafloor were made in 1914, and between 1925 – 1927 the German Meteor Expedition gathered over 70,000 ocean depth measurements using an echo sounder between Europe and the United States, leading to the discovery of the Mid-Atlantic Ridge.[4] In 1942, Harald Ulrik Sverdrup, Martin Johnson, and Richard Fleming published *The Oceans*, which was widely used as a textbook of oceanography. In the 1950s, August Piccard invented the bathyscape and used the *Trieste* to investigate the ocean depths. The nuclear submarine *Nautilus* made the first journey under ice to the North Pole in 1958. The theory of seafloor spreading and plate tectonics was developed by Harry Hammond Hess in 1960. The Ocean Drilling Project was started in 1966, and deep sea vents were discovered in 1977 by John Corlis and Robert Ballard in the submersible *Alvin*. In 1966, the National Oceanic and Atmospheric Administration was put in charge of exploring and studying all aspects of oceanography in the United States, and the National Sea Grant College Program was established to fund multidisciplinary researchers in the field of oceanography.[4,5,7]

The long coastline of Florida (3663 kilometers [2276 miles]), coupled with the uniqueness and complexity of its marine habitats, prompted the establishment of many oceanographic centers in south Florida. The Carnegie Institute Laboratory for Marine Biology was located in the Dry Tortugas from 1905 – 1939.

USGS

The Carnegie Institute Laboratory for Marine Biology was established on Loggerhead Key, Dry Tortugas, in 1905 and was one of the best-equipped tropical marine laboratories in the world. The facility closed in 1939.

In that laboratory, the foundations of tropical marine science in the Western Hemisphere were established. Pioneering researchers in the Dry Tortugas, led by the visionary Alfred G. Mayer, described and illustrated species of marine invertebrates, fish, and algae of the nearby coral reefs. Remarkably, these major accomplishments were made with relatively primitive field and laboratory equipment.

Other more recent centers of oceanographic excellence were established in south Florida, including the Rosenstiel School of Marine and Atmospheric Science (University of Miami), Harbor Branch Oceanographic Institute (Florida Atlantic University), Nova Southeastern University Oceanographic Center, and the National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratory. In addition, the Florida Institute of Oceanography was founded by the State of Florida University System to support and enhance Florida coastal marine science, oceanography, and related management programs through education, research, and public outreach.[8]

In recent years, emphasis has been placed on the development and application of computer models to further our understanding of oceanographic processes. The use of models allows numerical predictions of future ocean conditions based on past patterns.[9] Models have been used to predict ocean currents, algal blooms, distribution of fish and fish larvae, flushing times, salinity patterns, and coral bleaching. The development of new technologies, such as satellite tracked drifters and remotely operated vehicles, has opened new areas of exploration in the sea.

The deployment of arrays of oceanographic buoys and platforms and the use of remote sensing satellite technology have resulted in the availability of near real-time data and have facilitated modeling and forecasting of events, such as El Niño, algal blooms, and coral bleaching.[10] The Sustained Ecological Research Related to Management of the Florida Keys Seascape (SEAKEYS) Coastal-Marine Automated Network (C-MAN) stations were located throughout the Florida Keys and Florida Bay and provided an hourly record of wind speed, wind direction, air temperature, barometric pressure, sea temperature, salinity and solar irradiance. NOAA currently only supports the station located at Molasses Reef Lighthouse.

Oceanographic data are collected in many different ways

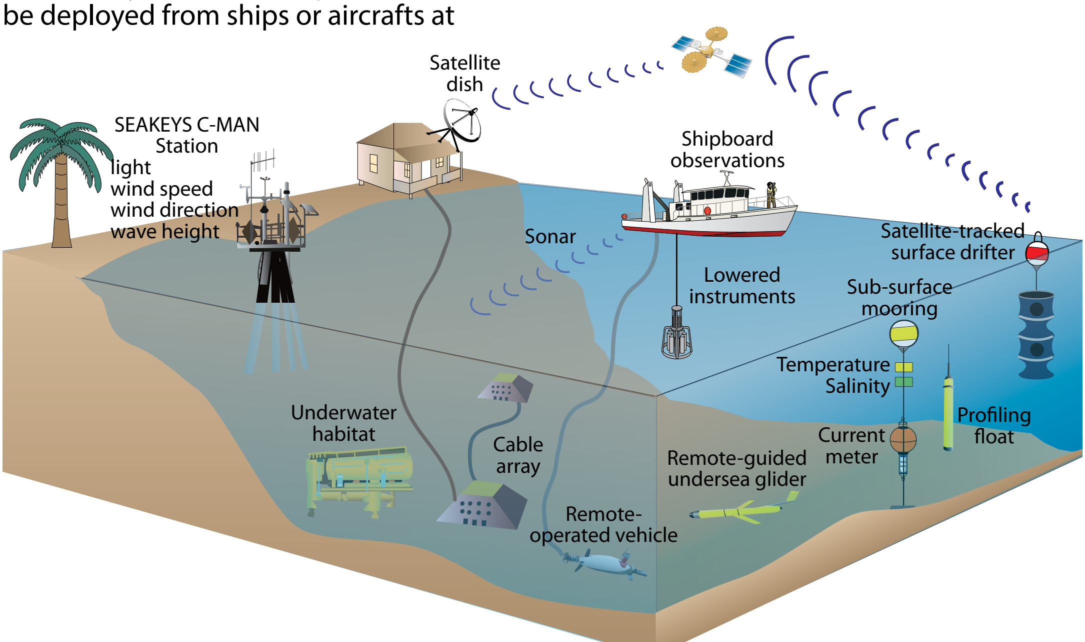
Ryan H. Smith and Elizabeth Johns

Scientists study the ocean in many ways. Seagoing oceanographers have historically conducted observations from research vessels. However, examining the physical, chemical, and biological properties of the ocean in that manner can be very expensive. Today, thanks in part to new technologies, scientists employ multiple tools to monitor our oceans. These methods are more economical and often provide greater coverage than traditional shipboard surveys. Although shipboard surveys are still important, they are one component in an ever increasing integrated ocean observing system.

Moored instrumentation arrays can provide long-term time series measurements at a fixed location. Other types of equipment designed to move freely through the ocean gathering data, such as surface drifters, Argo floats (i.e., broad-scale global array of temperature and salinity monitors), or gliders, can be deployed from ships or aircrafts at minimal cost. As these instruments gather data, they transmit this information back to scientists on land in real-time via satellite.

Scientists also gather data about the ocean remotely utilizing sensors affixed to orbiting satellites. Measurements such as sea surface temperature, ocean color, and sea surface height are collected continuously as these satellites pass over ocean regions.

Modeling is a very important component of modern oceanographic research. Scientists utilize computers to develop environmental models that mimic or reproduce the ocean conditions measured by the means just described. Accurate models, groundtruthed with real data, provide a tool for understanding ocean processes. Using these data (i.e., direct and remote measurements and model results), ocean scientists work to accurately describe the processes occurring in the marine environment and make predictions about the future.



Oceanographic data are collected in many different ways using instruments on the seafloor, throughout the water column, at the ocean surface, on land, and from space.

Oceanographic monitoring data are used to prepare ecoforecasts

James C. Hendee and Lewis J. Gramer

From the early 1990s – 2012, the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory (AOML) collaborated with the Florida Institute of Oceanography and the Florida Fish and Wildlife Research Institute in the management of data from the Sustained Ecological Research Related to the Management of the Florida Keys Seascape (SEAKEYS) Network. The network consisted of seven instrument-enhanced Coastal-Marine Automated Network (C-MAN) stations, cooperatively managed with the NOAA National Data Buoy Center (NDBC).

Instruments and data transmission equipment are still attached to all stations to measure standard meteorological variables such as wind velocity and direction, gusts, and air and dew point temperatures. Oceanographic variables, including salinity, sea temperature, tide height, and light attenuation (related to visibility) were formerly also measured throughout the network. However, due to budget constraints, the SEAKEYS components of the program have been decommissioned as of 2012, and only the station at Molasses Reef Lighthouse is still fully instrumented by AOML and NDBC. Data are collected hourly and transmitted to AOML from these stations via satellite. Scientists process and archive these data, then integrate them in time and space with other sources, such as satellite-derived sea surface temperatures and chlorophyll, and outputs from numerical computer models of the atmosphere and the coastal ocean.

Integrated data are used to develop marine ecosystem models called ecoforecasts, which assess changes in environmental conditions that trigger events such as coral bleaching, coral spawning, changes in water clarity and quality, larval drift, and other ecosystem phenomena. Ecoforecasts are validated, whenever possible, through observations from personnel in the field. Ecoforecasts allow managers at the Florida Keys National Marine Sanctuary to anticipate and understand changes to the ecosystem due to climatic and meteorological events. The knowledge gained from these forecasts support informed management decisions. These stations also provide the public with high quality, real-time information on air temperature, wind speed and direction (ndbc.noaa.gov), including sea temperature, salinity, and light data from Molasses Reef. To learn more about the network and to access the ecological forecasting database, please visit ecoforecast.coral.noaa.gov.

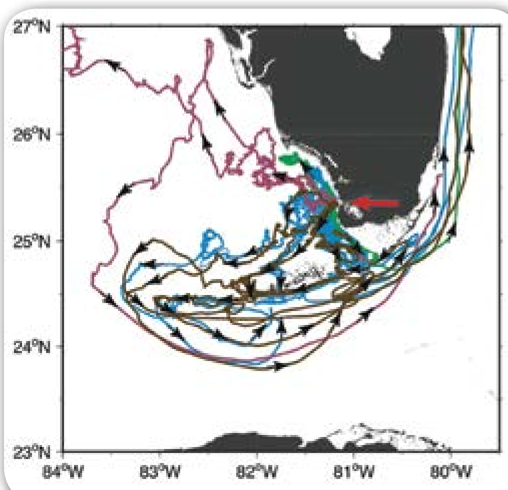
L. Myhre - Creative Commons

Real-time oceanographic data are collected from instruments fastened to the Molasses Reef Lighthouse and transmitted by satellite to the NOAA Atlantic Oceanographic and Meteorological Laboratory for analysis.

Ocean current circulation pathways are monitored by satellite tracking of drifters

Thomas N. Lee

Oceanographers deploy neutrally buoyant devices called "drifters" that are moved by ocean currents. Satellite tracking of drifters released in the surface waters of the Shark River discharge plume indicate that three common circulation pathways connect the upper level waters of the entire south Florida coastal system.



From Lee et al. (2002)

Combined plot of surface paths of drifters placed in the Shark River discharge plume (red arrow) during September 1994 – February 2000. Colors show seasonal pathways of flow: winter is blue; spring green; summer lavender; fall brown. The 20 drifter paths were distributed evenly over the seasons and tracked by satellite.

The primary pathways are either to the southeast and through the passes of the Middle Keys, which is most common during winter and spring, or southwest to the Tortugas during the fall. The time to reach the Florida Keys Atlantic Coastal Zone is 1 – 2 months for both routes. The third pathway is to the northwest in the summer and the eventual merger with the Loop Current segment of the Gulf Stream, followed by southward transport to the Tortugas. This movement takes place over a 3 – 6 month period. Drifter movements on the Southwest Florida Shelf for periods longer than 1 day result primarily from currents induced by the local winds combined with a mean southward flow toward the Keys. Surprisingly, all the drifters deployed in the Shark River discharge plume eventually entered the Florida Keys Atlantic Coastal Zone. After drifters reach the Keys Coastal Zone, they tend to either recirculate in Florida Current frontal eddies and wind-driven countercurrents for periods of 1 – 3 months or are caught up by the Florida Current and are rapidly removed from the south Florida coastal system.

NOAA

Oceanographers use drifters to track ocean current circulation patterns and pathways.

Knowledge of local current patterns is important in designing and locating Marine Protected Areas to maximize the retention of larval and juvenile forms of marine organisms within the region. In addition, larval and juvenile recruits are transported to south Florida from the Gulf of Mexico and Caribbean Sea via the Gulf Stream "conveyor" current system.

Living underwater allows scientists to collect data, test technologies, and make important observations

Ellen Prager

Aquarius is the only operating undersea research laboratory in the world. It is located in approximately 18.3 m (60 ft) of water in a sand patch at Conch Reef, about 5.6 kilometers (3.5 miles) offshore of Key Largo, Florida. Using saturation diving techniques, scientists can live and work underwater during 1 – 2 week missions, allowing them to make observations and conduct research that would be difficult or impossible by repeated dives from the sea surface. The undersea laboratory is part of the *Aquarius* Reef Base, which also includes an ocean observing station with real-time access via the Internet, and a shore base. The National Oceanic and Atmospheric Administration (NOAA) owns *Aquarius* and provides major funding for the facility through a grant to the operator, the University of North Carolina at Wilmington.


D.J. Roller - NURC

Aquarius provides state-of-the-art facilities for scientific research, technology testing, ocean observations, training, and education.

The mission of *Aquarius* Reef Base is as follows:

Scientific research: Research projects are performed to assess long-term change, study effectiveness of protected areas and restoration techniques, and further fundamental understanding of Florida coral reefs.


B. Campoli - NURC

Operations Manager Mark Hulsbeck inside Aquarius.

Technology testing: The facility serves as a test site for developing and applying new undersea technologies.

Ocean observations: Salinity, temperature, oxygen, waves, currents, and optical properties of the ocean are measured to provide valuable environmental data accessible in real-time over the Internet.

National training facility: The facility is used in training graduate and undergraduate students, U.S. Navy teams, and National Aeronautics and Space Administration astronauts.

Ocean education and outreach: The laboratory provides an exciting window into the underwater world and learning opportunities that students and the public can access at uncw.edu/aquarius.

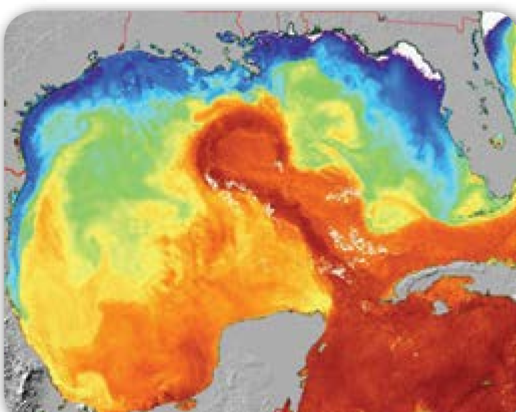

M. Ward - NURC

Aquarius Undersea Laboratory and ocean observing platform located off Key Largo. Scientists can live underwater for up to 2 weeks and transmit real-time data to a shore station or anywhere in the world via the Internet.

Frontal eddies are an important oceanographic feature in south Florida

Thomas N. Lee

Ocean eddies are rotating swirls of water that form along the boundaries of major ocean currents, such as the Gulf Stream. They come in different sizes, shapes, and rotation directions, ranging from large separations of the parent oceanic flows that form into warm- or cold-core rings several hundred miles across to small-scale turbulent vortices that engage in mixing fluids across the current boundary. Warm eddies have a clockwise rotation, and cold eddies rotate counterclockwise in the northern hemisphere.



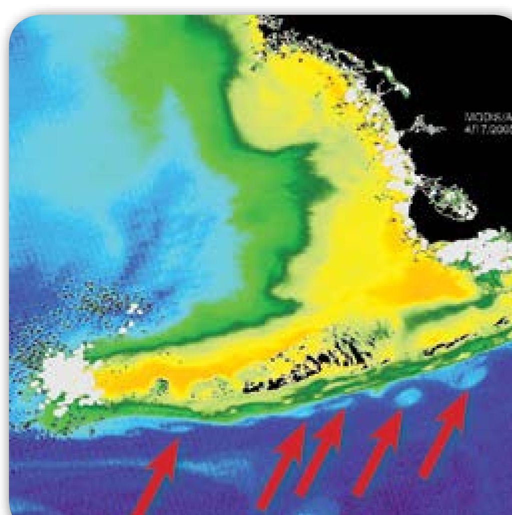
Courtesy of Johns Hopkins University

Satellite view of sea surface temperature in the Gulf of Mexico, March 21, 2001, showing Loop Current (dark red "finger") and cold water eddies (yellow swirls) from a 3-day composite image of sea surface temperature.

Eddies are particularly important to the health and wellbeing of the marine life and coastal waters of Florida because of the location and the peninsular shape of the Florida landmass. Florida is surrounded by one of the major ocean current systems in the world, the Gulf Stream system. A continuous stream of eddies move downstream along the shoreward boundary of the Gulf Stream system from the Gulf of Mexico, through the Florida Straits, and along the southeast coast of the United States to Cape Hatteras. These eddies are visible from space as cold, counterclockwise-rotating water masses that interact with the coastal waters of Florida and other southeastern states.

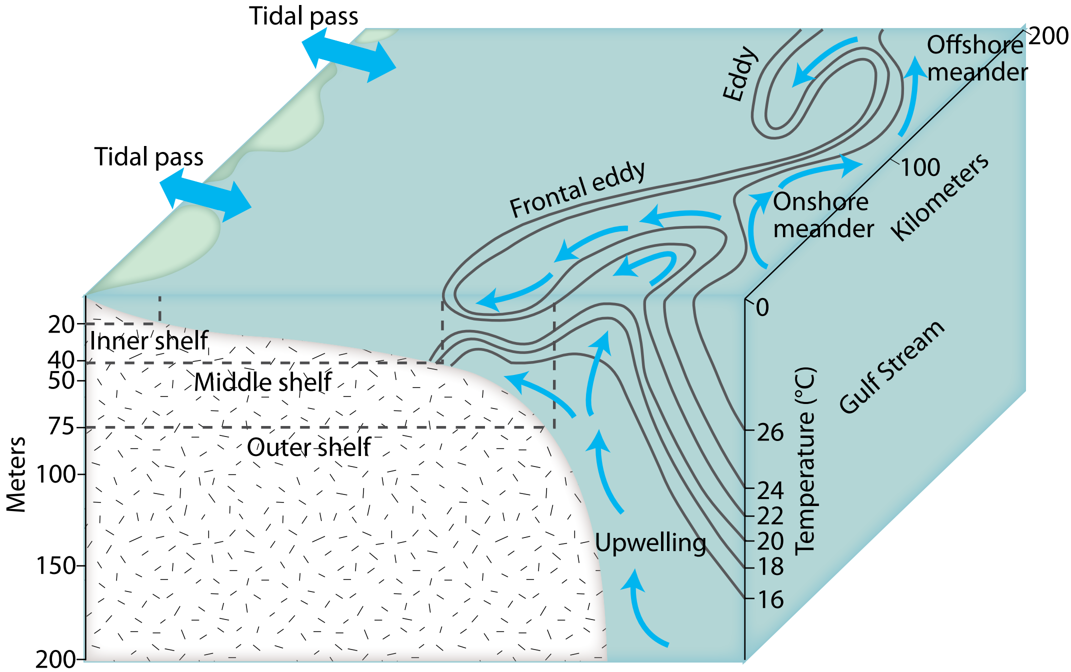
The eddies develop from growing disturbances of the Gulf Stream frontal boundary and hence are termed "frontal eddies." As the eddies grow within the space between the shallow coastal waters and the deep offshore waters of the Gulf Stream, the frontal boundary must shift offshore. The section of the Gulf Stream system that flows through the Gulf of Mexico from the Yucatán Channel to the Florida Straits is known as the Loop Current.

The Loop Current moves over deep, offshore water depths. Frontal eddies off the Loop Current reach diameters of 160 kilometers (100 miles) and move slowly toward the Florida Straits at only a few kilometers per day. On entering the



C. Hu - USF

NASA satellite image of south Florida showing frontal eddies that are spun off the Florida Current after it passes through the Florida Keys April 17, 2005.



Adapted from Lee, Yoder, and Atkinson (1991)

Schematic cross section of frontal eddy formation of the Gulf Stream system, showing onshore meander; offshore meander; and upwelling of cold, nutrient-rich water. Upwelling provides nutrients to surface waters, and eddies provide a retention mechanism for planktonic larvae.

Straits near the Dry Tortugas, the size of the eddies begins to decrease, and the forward speed increases. Reaching the Middle Florida Keys, where the Florida Straits channel turns to the north and decreases in width, the Florida Current (the section of the Gulf Stream system through the Florida Straits) is forced to converge toward shore, causing the eddies to undergo rapid elongation and downstream acceleration, reaching average speeds of 24 km (15 mi) per day. This represents the final decay stage for these large frontal eddies, some of which were born in the Gulf of Mexico near the Yucatán coast nearly 5 months previously only to shear apart into small-scale vortices in the Middle and Upper Florida Keys. However, the energy associated with their evolution is not destroyed and is later transformed into a rebirth of the larger frontal eddies north of Jupiter, Florida, as the Florida Current leaves the channel confines of the Florida Straits.

The cold interior waters of the eddies stem from upwelling of deeper, nutrient-rich waters of the Gulf Stream. Upwelling provides a basic food supply and nutrients that support ecosystem productivity within the eddies and adjacent coastal environments. Circulation within the eddies provides a retention mechanism for newly spawned larvae, which, combined with the available food supply, enhances the survival and condition of new recruits to the Florida Keys coastal waters and reef communities, including shrimp, lobster, and commercially and recreationally important fish species. For example, larvae spawned in the Tortugas Ecological Reserve can be spread all along the Florida Keys by the movement and evolution of the frontal eddies. Passage of frontal eddies also increases exchange of offshore waters of the Gulf Stream with coastal waters and thereby helps to maintain the clear, low nutrient waters of the coastal ecosystem.

Weather and climate strongly influence salinity, water quality, and circulation of south Florida coastal waters and bays

Elizabeth Johns and Thomas N. Lee

Weather and climate affect south Florida coastal waters and bays over a wide range of geographic space and time scales. The coastal system, made up of waters from the Gulf of Mexico, Atlantic Ocean, Florida Bay, Biscayne Bay, and other estuaries, is highly coupled. As a result, local meteorological processes, such as precipitation, evaporation, wind events, and direct inflows of freshwater through streamflow and runoff, strongly influence the salinity, water quality, and circulation of coastal waters.

Seasonal weather patterns

The south Florida climate is subtropical, with a relatively small annual temperature range but pronounced wet (summer/fall) and dry (winter/spring) seasons. During the wet season, showers occur virtually daily with the afternoon sea breeze, and tropical cyclones with counterclockwise winds are transient occurrences. During the dry season, cold fronts pass through the region approximately weekly with accompanying increased wind speeds and clockwise-rotating wind directions. This annual wet season/dry season pattern causes noticeable changes in the regional sea surface salinity, most pronounced in the coastal zone along the Southwest Florida Shelf near the river mouths and along the onshore edges of Florida and Biscayne Bays.

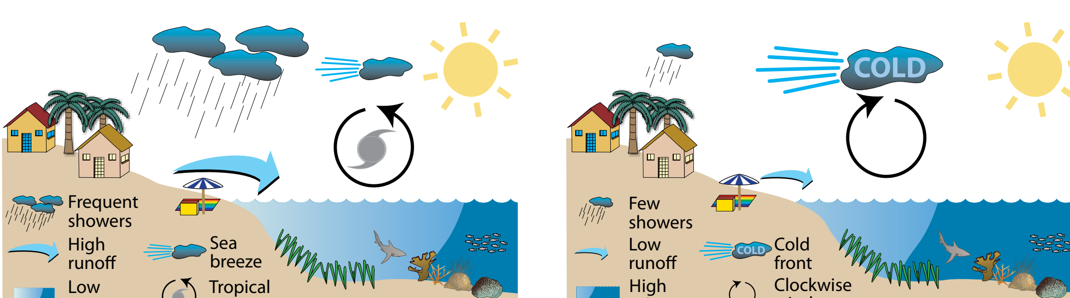
The seasonally changing regional winds, in conjunction with the geometry and bottom topography of the south Florida coastline, cause changes in the surface currents through direct forcing and by their effect on sea-level slopes. This subtidal circulation in response to the wind tends to be southward toward the Florida Keys in winter/spring, northwestward toward the Gulf of Mexico in the summer, and southwestward toward the Dry Tortugas in the fall. These seasonally episodic transport processes can affect the water quality of the Florida Keys coral reefs by delivering excessively warm, salty water to the reef tract from Florida Bay through the Keys passages in the spring and early summer, whereas relatively cold, turbid intrusions can occur in the winter.

Interannual to multidecadal weather patterns

Superimposed on the annual climatic cycle of south Florida are changes induced by longer-term and larger-scale influences, such as the interannual global phenomena known as the El Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), and the Atlantic Multidecadal Oscillation (AMO).

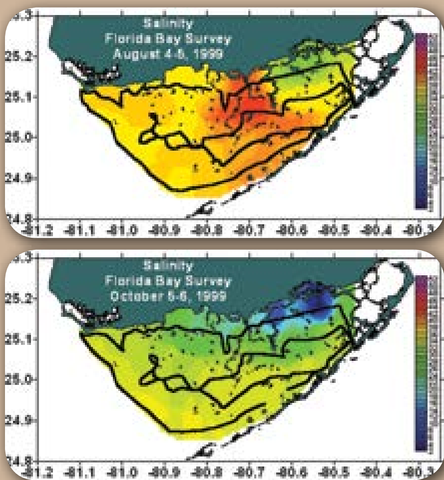
El Niño Southern Oscillation

The ENSO is a global ocean-atmosphere



Wet season (left) and dry season (right) variations in south Florida weather patterns.

Hurricanes and tropical storms



The most extreme meteorological events that affect south Florida are, as all Floridians well know, hurricanes and tropical storms. These episodic events cause rapid changes in barometric pressure; air and sea temperature; wind speed and direction; wave and swell amplitude, frequency, and direction; sea level height and slope; and coastal current speeds and directions. These changes also are accompanied by increased precipitation, more or less extreme depending on the size of the storms and the time that they spend over any given area of land or sea. All of these factors cause dramatic changes in oceanographic properties, including salinity of south Florida coastal waters, and tend to dominate time series records of meteorological and oceanographic parameters.

Surface salinity in Florida Bay before Hurricane Irene (1999) (top) and after Hurricane Irene (bottom). Red/orange shades indicate high salinities, and blue/green shades indicate low salinities.

phenomenon characterized by anomalously warm equatorial Pacific Ocean waters. It occurs roughly every 2 – 7 years. During its warm phase (El Niño), south Florida tends to experience a reversal of the normal wet/dry season and has cooler, rainier winters than usual. Conversely, during the opposite phase of ENSO (La Niña), when the equatorial Pacific is anomalously cool, south Florida tends to have warmer, drier conditions that often result in droughts and wildfires.

North Atlantic Oscillation

The NAO is an interannual north-south fluctuation in the sea level pressure difference between the Icelandic Low and the Azores High pressure systems. The NAO can cause noticeable variability in wind speed and direction, air and sea surface temperature, precipitation patterns, and the frequency and severity of storms.

Atlantic Multidecadal Oscillation

The AMO is a mode of sea surface temperature variability that occurs in the North Atlantic on a multidecadal time scale. The AMO is correlated with air temperature and precipitation variability over much of Europe and North America as well as with drought patterns and hurricane severity.

The ENSO, NAO, and AMO affect south Florida primarily by altering the usual seasonal temperature and precipitation cycles and have been shown to correlate with such variables as Florida stream flows, water depths in Lake Okeechobee, and coastal surface salinities.

Global climate change and implications for south Florida

Long-term changes in sea surface temperature, sea-level rise, hurricane severity and frequency, and other more recently discovered phenomena, such as a rise in ocean acidification, are expected to occur as a result of natural and anthropogenic global climate variability. South Florida likely will be dramatically affected by these changes due to its low elevation, high coastal population density, and unique sensitive ecosystems including the Everglades and the coral reefs. It remains to be seen how and to what extent the salinity, water quality, and coastal circulation of south Florida coastal waters, bays, and estuaries will be affected by global climate change.

Ocean currents connect south Florida coastal waters and link remote regions

Thomas N. Lee

South Florida coastal waters are highly connected throughout the region by a combination of locally produced circulation patterns and interactions with the surrounding large-scale Gulf Stream current system. The Gulf Stream system provides connections to remote upstream areas of the Gulf of Mexico and Caribbean.

The south Florida coastal region comprises subregions defined by their different physical characteristics, flow properties, and species composition. The subregions are the Southwest Florida Shelf, Ten Thousand Islands, Florida Bay, Florida Keys Atlantic Coastal Zone, and the Southeast Florida Shelf. The oceanographic linkage among the subregions depends on the degree of transport and interaction of currents connecting those subregions as well as on connections over the whole coastal region provided by the surrounding Gulf Stream currents and eddies. With the exception of the interior of Florida Bay, which is somewhat isolated by shallow banks, recent measurements of currents have shown a high degree of connectivity over the whole region as well as with remote upstream regions of the Gulf of Mexico.

Coastal water movements occur on time scales ranging from minutes to seasons to years. Tidal currents often account for a large part of the variation

Bathymetry of south Florida coastal waters and identification of coastal regions. Typical boundary of the Gulf Stream system surrounding south Florida is shown and identified as the Loop Current in the Gulf of Mexico and Florida Current in the Florida Straits. Evolution of frontal eddies is characterized along the Gulf Stream boundary.

in coastal currents and are important for local mixing and dispersion of materials. However, because of the reversing pattern of tidal currents, they are not effective transport mechanisms over distances longer than a few kilometers. Therefore, to understand transport by currents, oceanographers focus on currents that vary slowly and exist for periods of days to seasons. These are technically referred to as "subtidal currents." Subtidal currents are primarily responsible for linking adjacent, as well as remote regions to the south Florida ecosystem. These subtidal currents are mainly produced by interactions between local wind-forced currents, river runoff, and the large-scale Gulf Stream current system that encloses the south Florida coastal region. Subtidal coastal currents also are strongly influenced by local depth contours and coastline orientations. The major components of coastal currents within each of the subregions of the south Florida coastal ecosystem are described here.

Southwest Florida Shelf

The Southwest Florida Shelf is the southern extension of the wide, shallow West Florida Shelf that has smoothly changing depth contours aligned in a northwest-to-southeast direction. Similar to the West Florida Shelf, this region undergoes seasonal layering of the water column that is well mixed in fall and winter and vertically layered in spring and summer due to seasonal changes in the strength of wind mixing, atmospheric heating, and river runoff along its eastern border. The water on this wide shelf responds as a unit to alongshore (north or south) winds, with winds leading currents by less than 1 day. In other words, if the winds shift direction and come from the north, then shelf currents will start to move from north to south within 1 day.

Seasonal changes in wind strength and direction also produce seasonal differences in the strength of the currents, with greater strength of current variations in winter in response to passages of cold fronts and weaker currents in summer.

W.L. Kruczynski - EPA

The Dry Tortugas lie at the southern boundary of the Southwest Florida Shelf and are a main crossroads of ocean currents.

There is also a seasonal pattern in the upper layer currents, which are more southward in the winter, spring, and fall, changing to northward in the summer when winds shift to a northwesterly direction. The deeper lower layer currents are generally southward throughout the year. This is partly due to the Loop Current flow at the outer shelf, which is toward the south in this region following the Gulf Stream loop into the eastern Gulf of Mexico. The southward flow at the outer shelf creates sea-level slopes over the shelf that help to maintain the southward coastal currents and transport West Florida Shelf waters, including river discharges and harmful algal blooms, toward the sensitive habitats of the Florida Keys and Dry Tortugas.

At the southern extremity of the southwest coastal region lie the Florida Keys, including their westward extension out to the Dry Tortugas. The open passages between the Keys provide pathways to connect the Southwest Florida Shelf with the Florida Keys Atlantic Coastal Zone. The mean southward flow in the Southwest Florida Shelf coastal region discharges through the passages in the Middle Keys, predominantly Long Key

Channel and Moser Channel (Seven Mile Bridge), and onward toward the Florida Keys Reef Tract at a mean rate of about 28,000 cubic feet per second (cfs). This is a very large flow for a long-term average. The mean southward flow through the Keys passages appears to occur because mean sea level is higher in the eastern Gulf of Mexico than on the Atlantic side of the Keys, causing a cross-Key slope in sea level that forces flow through the passages. Recent measurements have shown a seasonal cycle in the southward mean flow, with strongest transports occurring during winter and spring, weak southward flow in summer, and mean northwestward flows into Florida Bay and the Southwest Florida Shelf region in fall. This seasonal cycle is the result of seasonal changes in local winds, which are the primary mechanism controlling the variability of sea-level slope across the Keys.

Ten Thousand Islands

The Ten Thousand Islands area is a shallow, complex system of small rivers, tidal creeks, and mangrove islands that receive freshwater runoff from the Everglades, primarily through Shark River, Broad River, and Lostmans River. Their combined discharges form a nearshore band of low salinity water that follows the curved shoreline northwest to Cape Romano. This low salinity band is transported toward the southeast and into western Florida Bay by the mean southward coastal flow and helps to prevent high salt concentrations (hypersalinity) from developing within western Florida Bay.

W.L. Kruczynski - EPA

Mangrove islands are found throughout Florida Bay.

Florida Bay

Florida Bay is made up of a complex maze of shallow basins separated by mud banks and mangrove islands. The Bay is openly connected to the Southwest Florida Shelf along its wide western boundary, but exchange with the Florida Keys Atlantic Coastal Zone is restricted to a few narrow tidal channels through the Keys island chain. The northern boundary of the Bay is mangrove fringed, with freshwater input into the northeastern region predominantly through Taylor Slough and Trout Creek.

The rapid decrease in tidal range in Florida Bay with distance from the western boundary and the dramatic increases in salinities observed in the north-central interior basins are indicative of poor water exchange between basins. Thus, it takes a long period of time for basin waters to be renewed. Freshwater flows from the Everglades directly into the northeast subregion of Florida Bay. These lower-salinity waters are mostly trapped by the enclosing shallow banks and have minimal influence on the high salinities of the surrounding subregions. Western basins receive Everglades discharge from Shark River and the Ten Thousand Islands, but in a diluted form mixed with waters from the Southwest Florida Shelf.

The amount of freshwater flow discharging from the Everglades through the Ten Thousand Islands and Florida Bay averages about 3000 cfs, which is small compared with the estimate of the mean southward flow connecting the Southwest Florida Shelf and Florida Keys Atlantic Coastal Zones. Therefore, it is unlikely that increasing the freshwater flow to the Everglades will have a substantial impact on waters of the Southwest Florida Shelf or Florida Keys Atlantic Coastal Zone. However, an increased Everglades flow should cause considerable modification of salinity within Florida Bay from increased discharges into northeast Florida Bay via Taylor Slough and Trout Creek and into western Florida Bay through the southeastward movement of the Shark River low salinity plume. Diverting a portion of the increased Everglades discharge into McCormick Creek that connects to the north central region of the Bay would greatly aid in reducing hypersaline conditions that develop in the central Bay during the dry season.

Florida Keys Atlantic Coastal Zone

This zone consists of a narrow, curving shelf with complex topography associated with the Florida Keys Reef Tract. The curving shoreline causes regional differences in current patterns in response to prevailing easterly winds and influences of the Florida Current, the portion of the Gulf Stream system from the Florida Straits to Cape Hatteras. Westward currents are persistent at the bank reef tract and Hawk Channel areas of the Lower Keys in response to winds from the east. In the Upper Keys region, these same winds blow onshore and have little effect on alongshore currents. The Middle Keys are a transition region.

The seasonal cycle of the winds results in a seasonal change in coastal currents that is most pronounced in the Upper and Middle Keys where northward flows occur in the summer during southeasterly winds, and southward flows occur in fall, winter, and spring due to winds from the northeast and east. Mean coastal flows in the Lower Keys are toward the west throughout the year because the westward-oriented coastline aligns with the prevailing winds from the east and southeast.

Water properties and currents in the Florida Keys Atlantic Coastal Zone are also highly influenced by the interaction with the Gulf Stream system (Florida Current) and the evolution of eddies that travel downstream along its shoreward boundary. Large, counterclockwise-


W.L. Kruczynski - EPA

Water moves from the Southwest Florida Shelf to the Florida Keys Atlantic Coastal Zone through tidal passes, such as Bahia Honda Pass.

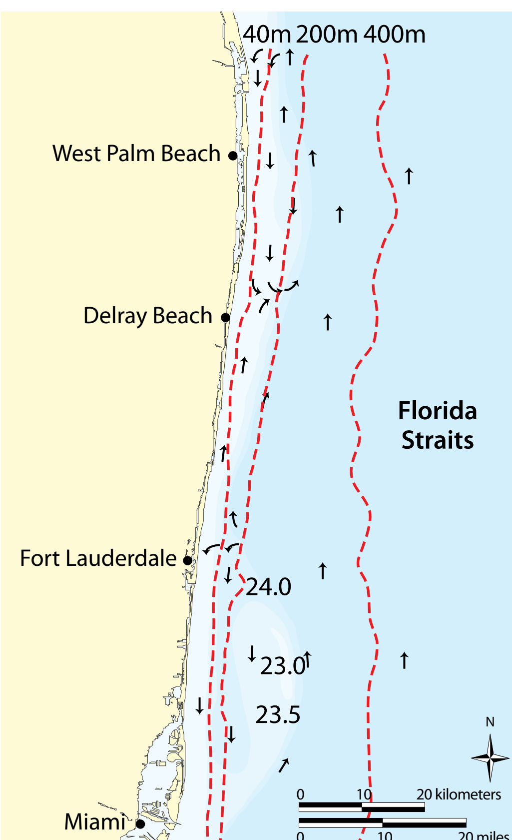
rotating eddies with diameters of 100 – 200 kilometers (62 –124 miles) move downstream along the frontal boundary of the Loop Current in the eastern Gulf of Mexico. On reaching the Dry Tortugas region, these eddies can remain nearly stationary for several months and are sometimes referred to as Tortugas Eddies. After this period, they continue their movement into the Lower Keys and follow the northward curve of the Florida Current toward the Upper Keys with decreasing size and increasing forward speed. These features can occur any time of year, intensifying the westward countercurrents in the Keys. Mean flows at the seaward edge of the reef tract are directly related to the offshore distance of the Florida Current. Stronger downstream (northward) flows occur in the Upper Keys because of the proximity of the strong northward-flowing Florida Current along the outer shelf. Greater upstream (countercurrent) flows occur in the Lower Keys because of three factors: the Florida Current is located farther offshore on average, there are larger and more persistent eddies, and the winds are predominantly toward the west in the same direction as the countercurrent and align with the shelf topography.

Southeast Florida Shelf

The Southeast Florida Shelf is made up of a long, narrow coastal zone squeezed between the highly developed southeast

Florida metropolis at the shore and the strong northward flowing Florida Current at the shelf break. The shelf stretches north to south 100 km (62 mi) from Biscayne Bay to Palm Beach. The shelf configuration is unusual in that it is extremely narrow, varying in width from 1 – 3 km (0.6 – 1.9 mi) and quite shallow, with only a 30 meters (100 feet) water depth at the shelf break.

In nearshore waters of less than 10 m (33 ft), flow and temperature variations are controlled by tidal and atmospheric influences, typical of most shallow shelves. Northerly or southerly winds have the greatest influence on the direction of currents of this north-south-oriented coastline. The current response is in the same direction as the wind (north or south) with a lag of less than 12 hours. Typically in the summer, the nearshore mean current is toward the north due to the prevailing southeast winds. Prolonged north wind events in the fall result in southward mean flows at the coast. Winter and spring cold front passages cause variable alongshore flows without a consistent pattern.

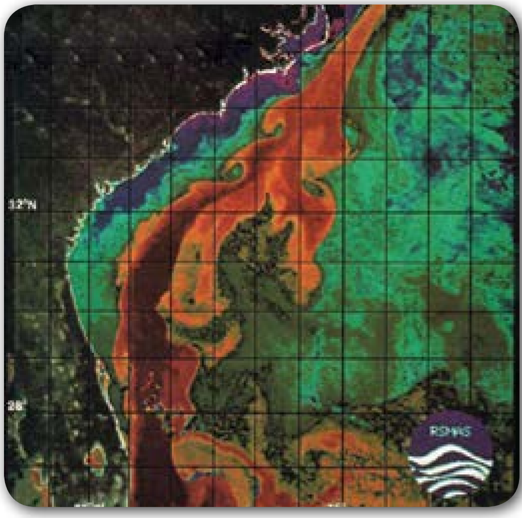


Composite map of sea surface temperature (°C) from continuous shipboard measurements for the period February 20 – 23, 1973, showing two Florida Current frontal eddies interacting with coastal waters of the Southeast Florida Shelf. Arrows indicate observed current directions. Red lines are depth contours.

Current and water properties of the mid- to outer-shelf regions tend to be strongly influenced by the nearby Florida Current. Seaward of the shelf break, there occurs a submerged terrace at depths of 200 – 300 m (656 – 984 ft) that extends eastward for another 20 km (12 mi) before plunging to the 700 m (2300 ft) depths of the Florida Straits. The width of the Florida Straits along this shelf domain is only about 75 km (47 mi) and behaves as a channel to restrain the meandering movements of the Florida Current to typically 5 – 10 km (3 – 6 mi) and generally less than 20 km (12 mi). However, the Miami Terrace, which extends into the body of the Florida Current flow, can perturb the flow, causing meandering and eddy development along the shoreward boundary of the current, resulting in strong interactions between the Florida Current and adjacent shelf waters.

Typically the shoreward front of the Florida Current follows the shelf break northward, causing strong northward mean flows over the outer shelf ranging 25 – 50 centimeters per second (0.5 – 1.0 knots). Flow and temperature variabilities within the mid- to outer-shelf regions are dominated by the northward passage of small, counterclockwise-rotating frontal eddies that occur at an average frequency of once per week throughout the year with little seasonal change. Eddy diameters range from 5 – 30 km (3 – 19 mi) and their passage through the outer shelf can cause upwelling of deeper, nutrient-rich waters of the Florida Current that stimulate primary production in surface waters along the continental slope. Eddy passages normally take 1 – 2 days and result in considerable exchange between resident shelf waters and

Florida Current waters within the eddy. Displacement of shelf waters by eddies at an average weekly interval represents a flushing mechanism that results in mean residence time of shelf waters of 1 week.



Lee, Yoder, and Atkinson (1991) prepared by O. Brown and R. Evans - UM/RSMAS

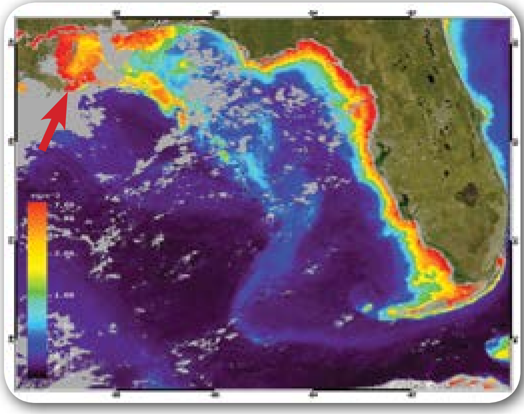
Satellite Advanced Very High Resolution Radiometer thermal image of the Gulf Stream on April 23, 1980, showing eddy development off the Florida Current along the Southeast Florida Shelf.

At times, these eddies have their origins on the Gulf Stream front in the Gulf of Mexico and together with the background flows of the Florida Current and coastal regions serve to connect the Southeast Florida Shelf with the previously mentioned shelf domains of the Florida Keys Atlantic Coastal Zone and the Southwest Florida Shelf as well as with other upstream sources such as river discharges. At other times, the eddies can be generated locally by unstable meander motions of the Florida Current. As the eddies leave the Southeast Florida Shelf region and move northward along the Southeast United States Continental Shelf, they leave the confines of the Florida Straits and the Gulf Stream frontal meanders are free to grow, resulting in explosive eddy growth that can reach dimensions of 100 – 200 km (62 – 124 mi) in a matter of days. Eddy development and migration along the shelf serve as a nutrient pump to outer shelf waters from Florida to Cape Hatteras, stimulating primary production.

Subregions are connected and linked to remote regions

The south Florida regional current patterns form a tightly coupled recirculation system. This recirculation system provides an excellent opportunity for successful recruitment of locally spawned larvae. Foreign recruits can also arrive via the Gulf Stream "conveyor" from upstream locations in the Gulf of Mexico and Caribbean.

The rapid movement of the Gulf Stream Current can also bring unwanted pollutants from the Mississippi River watershed and the wider Caribbean. Occasionally, Mississippi River discharge is transported south to the Keys in a low salinity band on the shoreward side of the Florida Current. The southward transport occurs when either the Loop Current or a large eddy separated from the Loop Current interacts with the river discharge off the Mississippi delta. Transport time to the Keys is less than 1 month and can result in decreased salinities and increased turbidity at the Florida Keys Reef Tract. Toxic chemicals, such as pesticides, were found in an intrusion of Mississippi River water following the 1993 Mississippi flood event.



C. Hu - USF

Satellite image showing chlorophyll concentrations. Water from the Mississippi River Delta (red arrow) can be traced flowing through the Florida Straits and past the Florida Keys Reef Tract. High chlorophyll concentrations shown in red, and low chlorophyll concentrations are shown in black to violet hues.

Water circulation and renewal in Florida Bay is influenced by flows from the Southwest Florida Shelf and tidal passes

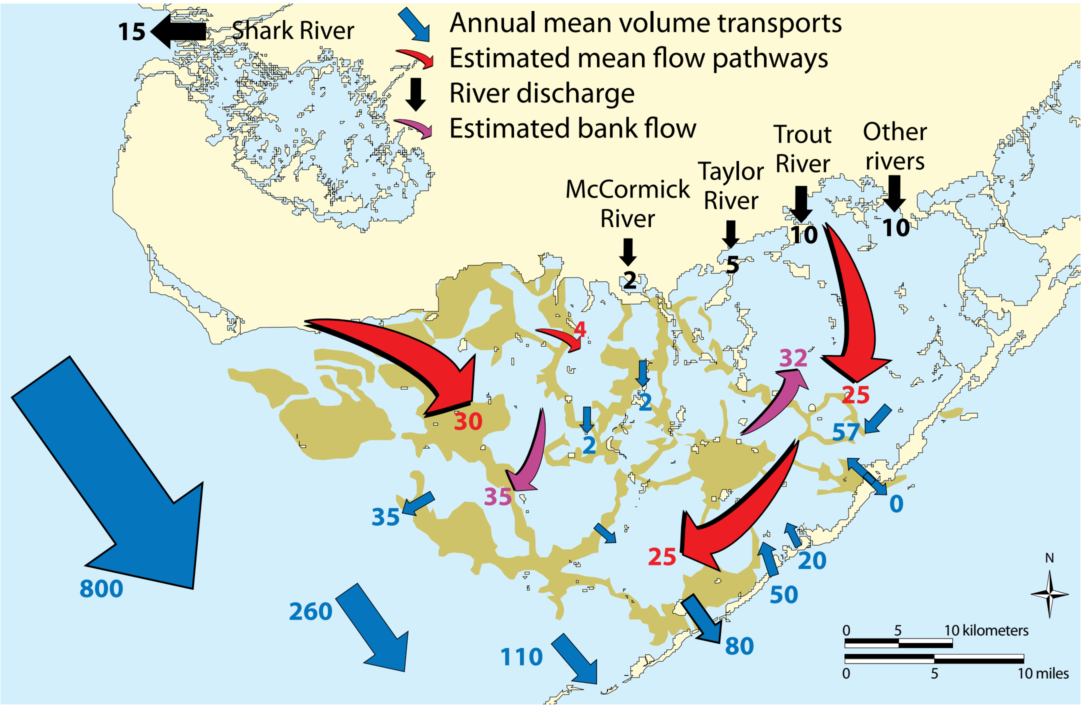
Nelson Melo and Thomas N. Lee

Florida Bay is located at the southern end of Everglades National Park between the mainland and the Florida Keys. The Bay waters interact with adjacent coastal waters of the Southwest Florida Shelf to the west and Florida Keys Atlantic Coastal Zone to the east and southeast. Exchange of Bay interior waters with the Florida Keys Atlantic Coastal Zone is restricted to a few narrow tidal channels in the Keys island chain between Key Largo and Islamorada, whereas water exchange with the Southwest Florida Shelf region takes place across a 40 kilometer (25 mile)-wide open boundary. The combined tidal harmonics of the Gulf of Mexico and the Atlantic produce a mixed tide along this wide western boundary with a tidal range of 1 – 1.5 meters (3 – 5 feet).

Surprisingly, the largest tide in the Gulf of Mexico or on the eastern seaboard of the United States south of Brunswick, Georgia, occurs at the mouth of Shark River. There the tidal range can reach over 2 m (6.5 ft) during spring tides. Not surprising then, Flamingo Channel, which is the northwest entrance to the Bay and only about 10 km (6 mi) from the mouth of Shark River, is the largest open channel to the Bay and has the greatest tidal exchange. The northern boundary of the Bay is fringed with mangroves and coastal lagoons. Freshwater discharge to the Bay is primarily confined to the northeastern region through Taylor Slough and Trout Creek.

The interior of the Bay is made up of a complex network of shallow basins with depths ranging from 1 – 3 m (3 – 10 ft) deep separated by mud banks and mangrove islands. Connection between basins occurs through narrow channels and over the shallow banks. Water depths over the banks are typically less than 0.3 m (1 ft) deep. During periods of low sea level (e.g., winter dry season or strong winds toward the west or southwest), the banks can become exposed, causing

Satellite image of Florida Bay showing the four subregions based on water circulation patterns and water quality.



Annual mean volume transports (m^3/s) in Florida Bay and through the Keys (blue arrows) and estimated mean flow pathways (red arrows) between Florida Bay subregions. River discharge is shown by black arrows. Estimated bankflow is shown by magenta arrows.

further isolation of the interior basins. The mud banks are also primarily responsible for the large landward falloff in tidal range, which decreases from 1.5 m (5 ft) at the open western connection of the Bay to a few centimeters (1 inch) near the northeast boundary of the Bay.

The typical climate of south Florida consists primarily of two seasons: a dry season during winter/spring and a wet season during summer/fall. The balance of freshwater flux, controlled by river discharge, precipitation, and evaporation, is negative during the dry season and positive over the wet season. This leads to increasing salinities in Florida Bay during the dry season and decreasing salinities in the wet season.

The configuration of mud banks and mangrove islands within Florida Bay and differences in the magnitude of volume exchange with adjacent waterbodies together with the isolation of river discharge into the northeast portion of the Bay tend to separate the Bay into four subregions: northeast, north central, southeast, and western.

The subregions of Florida Bay are characterized by prolonged hypersalinity in the north central part and persistent lower salinity in the northeast, with both subregions displaying a large seasonal range of salinity. Salinity of the southeast and western subregions is more typical of the adjacent coastal areas, indicating enhanced water exchange with these regions.

Recent direct measurement of volume transports through channels connecting interior basins have been used together with time series of basin total volume transport derived from sea level measurements to estimate basin flushing rates and residence times and to identify the important physical processes regulating the water renewal. The measurement strategy was applied to the north central, northeast, and western subregions and clearly shows that local wind forcing is the primary flushing mechanism controlling basin residence times. South Florida winds typically are weak from the east and southeast during the summer, shifting to be more from the northeast during the fall, with increased strength of wind events that can last several days. During the winter and spring seasons, cold fronts move through the region within a period of 3 – 7 days, causing increased winds that rotate clockwise from southwest through northwest to northeast. The cumulative effect from the passage of these wind events drives a mean flow through the basins, with net inflows over the banks and net outflows through the channels. The resulting net basin throughflows are weak and require on the order of 1 year to replace an equivalent mean volume of the north-central and northeast basins.

T. Scott - FGS

Florida Bay comprises a complex network of shallow basins with depths ranging from 1 – 3 m (3 – 10 ft) deep. These basins are separated by mud banks and mangrove islands and are connected by narrow channels through the shallow banks.

Net basin throughflows were found to be significantly larger in the western basin, which resulted in enhanced water exchange with the adjacent coastal waters, moderation of seasonal changes in salinity, and short residence times ranging from 0.5 – 2 months. Estimates of seasonal water balance indicate that groundwater discharge to Florida Bay is negligible.

Florida Bay mean flow pathways were estimated from annual mean volume transport measurements, river discharges, and derived bank flow estimates. The annual river discharge to the Bay of 27 cubic meters per second essentially is trapped in the eastern part with little diluting influence on hypersalinity of the north central Bay. Reduction of hypersalinity events in the Bay and corresponding degradation of water quality will require a diversion of a portion of the river discharge to the central region via McCormick Creek. There is a weak mean flow pathway from Flamingo Channel eastward across the northern banks and then southward through the north central basin of 4 m^3/s. There is also a much stronger clockwise mean flow pattern of about 30 m^3/s from the major arm of Flamingo Channel that feeds an outflow through Rabbit Key basin and through the channels of Nine Mile Bank. However, this recirculation through the western basins is small compared with the 800 m^3/s net southward coastal flow that provides the connection to transport riverine discharges from the Southwest Florida Shelf and Ten Thousand Islands area (including Shark River) to the western basins of Florida Bay and ultimately the Florida Keys Reef Tract.

T.A. Frankovich - FIU

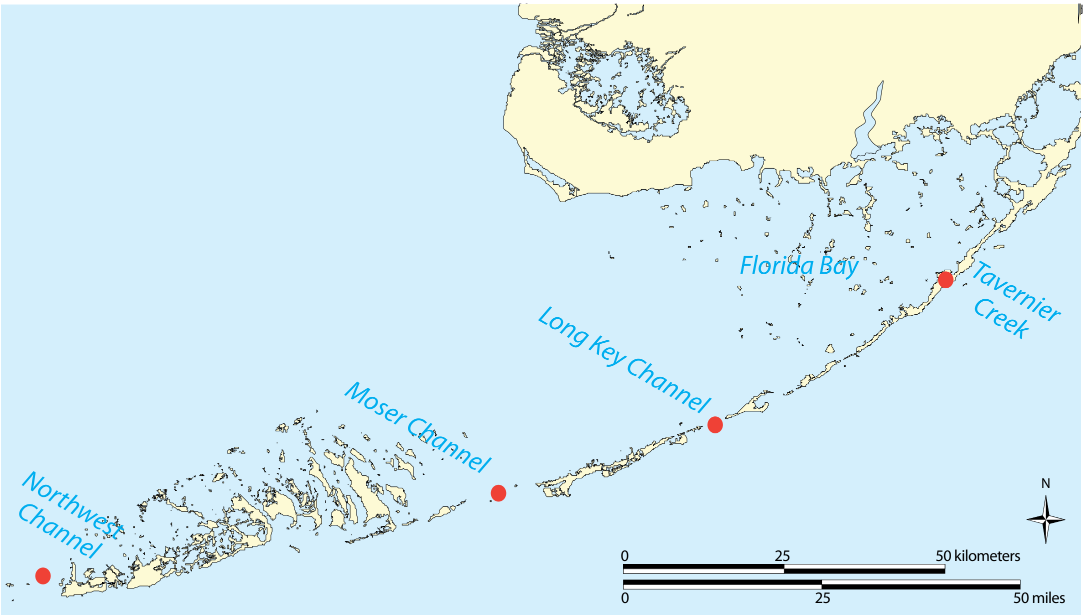
Narrow channels through the shallow banks are marked with paired aids to navigation within Everglades National Park.

Tidal flow and current reversals transport larvae spawned in the Atlantic Ocean to nursery grounds in the Gulf of Mexico

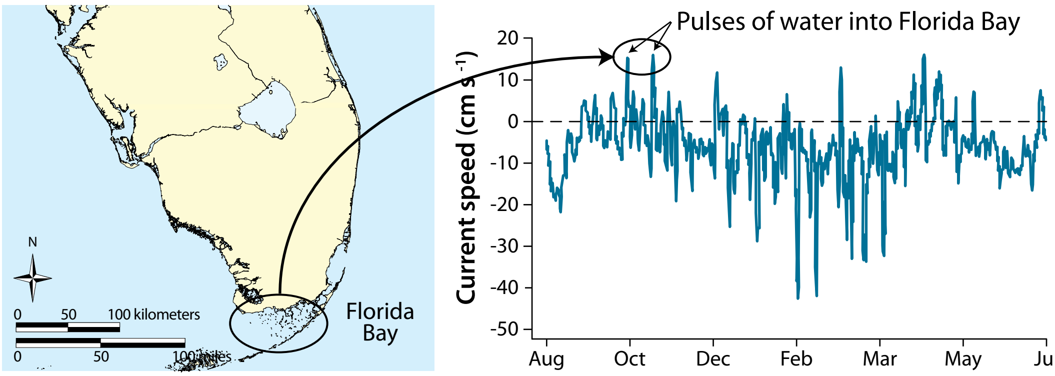
Ned Smith

Slightly higher water levels on the Gulf side of the Florida Keys result in a persistent, long-term net flow of water from the Gulf of Mexico to the Atlantic Ocean through the tidal passes between the Keys. Many animals, including spiny lobsters, pink shrimp, tarpon, and goliath grouper spawn in the Atlantic Ocean but have nursery grounds on the Gulf side of the Florida Keys and in Florida Bay. How do their planktonic larvae travel against the long-term net outflow of water from the Gulf to the Atlantic? There are two mechanisms that allow this transport to occur. One involves the ebb and flood of the tide, and the second involves temporary wind-driven reversals of the Gulf-to-Atlantic flow.

Strong ebb and flood tidal currents occur through all the major channels in the Upper and Middle Keys every 12.4 hours. Thus, although the long-term net flow is toward the Atlantic, Atlantic water, including any larvae suspended in the water column, is carried several kilometers into Florida Bay on the Gulf side of the Keys with each flood tide. Mixing of Atlantic and Bay waters during the flood half of the tidal cycle causes some Atlantic water to remain in the Bay. In its place, Bay water leaves on the following ebb. With this exchange, larvae are transported in the direction of the nursery areas. On the next flood tide, the larvae within Florida Bay are carried still further into the Bay, and with more mixing, some of them will be left behind on the following ebb. By entering the Bay with the flood currents from the Atlantic and then exiting with the ebb currents to the Gulf, larvae can move upstream against the long-term net Gulf-to-Atlantic movement of water. This transport mechanism is in operation throughout the year, and the cumulative effect on larval movement is believed to be significant.



Location of tidal passes where wind-driven reversals of nontidal currents were observed (red dots). Reversals result in inflow into Florida Bay at Moser Channel, Long Key Channel, and Tavernier Creek. Wind reversal temporarily halts movement toward Florida Bay in the Northwest Channel.



Nontidal current speeds (tidal floods and ebbs removed) recorded in Long Key Channel (August 20, 1995, to July 21, 1996). Negative speeds (below the dashed line) represent water leaving Florida Bay. Arrows point to two of the 30 pulses of Atlantic water entering Florida Bay. For comparison, flood and ebb current speeds are commonly 45 – 55 centimeters per second (approximately 1 knot). The total current speed is the sum of tidal and nontidal components. Major periods of wind-induced reversals occur in late fall and spring when many species are spawning.

The second mechanism involves temporary reversals of the Gulf-to-Atlantic movement of water due in part to changing wind conditions. The nontidal flow of water through the passes separating the Keys reverses over time periods of a few days, sending pulses of Atlantic water to the Gulf side of the Keys. Strong southeasterly winds raise water levels on the Atlantic side and reinforce the flood currents. On the Gulf side, the same southeasterly winds lower water levels and help to draw water out of the Bay on the ebb tide. Wind forcing is especially important in the shallow waters of Florida Bay.

In a study conducted in Long Key Channel, numerous reversals of the nontidal current were observed over a 336-day period. The net movement of water was consistent with the Gulf-to-Atlantic transport, but 18% of the observations recorded an inflow to Florida Bay. The nontidal current reversed 30 times during the study to send pulses of Atlantic water into the Bay. Reversals occurred throughout the study, but they were more frequent in late fall and late spring, times when larvae of many species are numerous.

Studies conducted in other channels in the Middle and Upper Keys revealed inflow to be even more common. For example, during a 339-day study in Tavernier Creek, a nontidal inflow to the northeast corner of Florida Bay was found in 33% of the observations. During a 254-day study conducted in Moser Channel under the Seven Mile Bridge, a nontidal inflow was recorded 47% of the time.

The long-term net outflow found in the Upper and Middle Keys does not occur in the Lower Keys. In a 348-day study conducted in the Northwest Channel just west of Key West, a northward nontidal transport toward Florida Bay occurred 73% of the time. At this location, larvae are transported to Gulf nursery areas with the mean flow. Wind events play an important role, but in Northwest Channel, they temporarily halt the import of water to the Bay.

In summary, the average west-to-east movement of water is an important feature of the regional circulation. A closer look at nontidal flow through the channels that separate the Florida Keys reveals that temporary reversals occur regularly. In the Upper and Middle Keys, these reversals can help to explain the apparent upstream movement of larvae into and through Florida Bay. Wind-driven transport together with the stepwise tidal transport play a crucial role in the life cycles of species that are spawned in the Atlantic Ocean and grow up on the Gulf side of the Florida Keys.

Many planktonic larvae use tidal currents to migrate or maintain their position

William L. Kruczynski and Pamela J. Fletcher

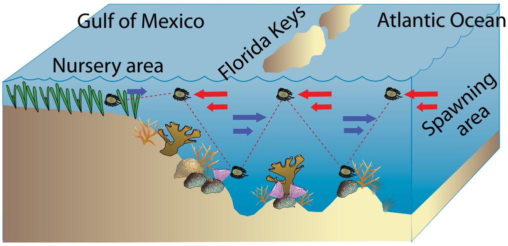
Many planktonic forms have limited mobility and are at the mercy of currents to control their distribution. However, other planktonic forms have the ability to migrate vertically and horizontally in the sea in response to environmental cues.

Vertical migration

Zooplankton, including adult and larval forms of crustaceans, salps, jellyfish, fish, squid, and other animals that live in the open ocean (blue water) perform daily vertical migrations by adjusting their buoyancy in response to light cues. They spend daylight hours at depths with little or no light penetration (aphotic zone) and migrate to the surface to feed during dark hours. This activity concentrates food sources at night and makes the surface waters an "eat or be eaten" environment. Also, excretion of nitrogenous wastes by the nightly migrants at the surface stimulates new primary production by phytoplankton during daylight hours.

Horizontal migration

Many organisms, including lobster, goliath grouper, and shrimp, spawn in the open ocean and settle out of the water column as juveniles in hardbottom, seagrass, and mangrove habitats on the Gulf of Mexico side of the Florida Keys. How do they get there? Larvae and postlarval forms are passively moved toward the Gulf by riding daily tidal currents and during times of periodic, wind-driven current reversals. But, how do they hold their position during unfavorable current conditions? The larvae are not as passive as once believed. They are able to adjust their buoyancy in response to current cues and seek refuge from unfavorable currents by migrating to protected benthic shelters, such as sponges and reefs. When currents become favorable again, they rise toward



Animals, such as Caribbean spiny lobster and goliath grouper, spawn in the Atlantic Ocean near the bank reef. Larvae are planktonic (i.e., float with the currents) but are capable of raising and lowering their position in the water column to "ride" tidal currents flowing toward the Gulf of Mexico. They find shelter near the bottom, out of the current, during periods of unfavorable flow direction and rise in the water column when the flow direction again becomes favorable. In this stepwise progression, they are capable of moving against the long-term flow and toward their nursery areas in seagrass, sponge, and mangrove communities on the Gulf side of Florida Keys and Florida Bay. Red arrows represent flooding tides toward the Gulf; blue arrows ebbing tides flowing to the Atlantic.

the surface to continue their migration to nursery habitats. This same mechanism allows larvae spawned in shallow waters to stay in the home range of their parents during daily tidal reversals.

Implications for planning Marine Protected Areas

The movement of larvae into and out of no-take marine reserves plays an integral role in determining whether reserves can sustain themselves, exchange larvae with other protected sites, or supplement surrounding fished areas. A thorough scientific understanding of the larval dispersal methods of species protected in reserves is required in the effective design and placement of protected areas. Are larvae coming from long distances? Do they require protected habitats en route? Or are larvae "self-seeding" from local sources? For species capable of horizontal migration, it does not make sense to protect spawning habitat but not protect nursery habitat when both are required for the conservation of the species.

Hydrodynamic models provide insight into regional circulation patterns

Villy H. Kourafalou

The Florida Keys and the adjacent coral reefs are on a narrow continental shelf that quickly deepens to the Florida Straits located between south Florida and Cuba. The Gulf Stream is the dominant feature of oceanic circulation near the Keys and has several geographic names. Along the Keys it is appropriately called the Florida Current, and it receives flow from the Loop Current from the Gulf of Mexico. These currents are part of a larger-scale oceanic current system that enters the Gulf from the Caribbean Sea through the Yucatán Strait.

Sea surface height maps graphically show variability due to oceanic currents and depict highs and lows of the ocean surface, which give important clues about the circulation. Frontal areas have strong contrasts of sea surface height, and closed highs or lows mark recirculating features, the so-called eddies that are cyclonic (rotate counterclockwise) around a low and anticyclonic (rotate clockwise) around a high.

Understanding ocean circulation

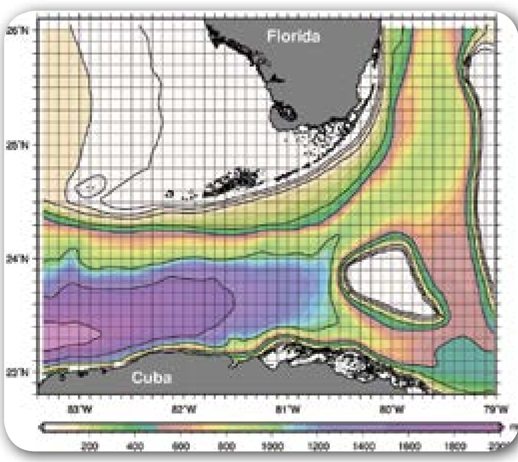
Two mechanisms are of utmost importance for marine life and water quality along the Florida Keys Reef Tract. First, because the Keys shelf is narrow and it neighbors the Florida Straits, the waters around the Keys are strongly influenced by the Florida Current, which is influenced by the Loop Current and by a much larger oceanic current system. Second, eddies traveling along the ocean currents carry nutrients, larvae, and sometimes pollutants from upstream sources that can be from hundreds of kilometers away. As these enter the Straits, they interact with the rough topography of the Keys that often causes them to break apart, delivering the substances and particles that have been traveling along entrapped in their recirculation. Both mechanisms are of utmost importance for marine life and water quality along the Florida Keys Reef Tract. Oceanographers observe these phenomena through *in situ* and satellite measurements and have developed hydrodynamic numerical models using these data.

Hydrodynamic numerical models

Hydrodynamics deal with the physics of the waters (e.g., motions, circulation); numerical means that equations are used to describe these phenomena and are solved through computer coding; and model means that a series of equations and coding methods are used to describe (i.e., model) the physical system. There are many different models that the oceanographic community uses widely, and they differ in the phenomena they target, the methods of solution they use, the ways they describe the interactions of the ocean with the atmosphere, and the ways they "discretize" (i.e., divide in smaller parts) the model domain. A local example is the Florida Keys Hybrid Coordinate Ocean Model (FKEYS-HYCOM), which covers all coastal areas around the Florida Keys and the deep Florida Straits, extending to Cuba and the Bahamas. The FKEYS-HYCOM is coupled with a biological model that allows the study of coral fish recruitment in the Florida Keys. There are also biogeochemical models that deal with the nonphysical phenomena and coupled physical and biogeochemical models (or full ecosystem models) that deal with all possible phenomena in oceanography.

Hydrodynamic models simulate environmental conditions

Hydrodynamic models simulate (i.e., model) natural phenomena. They synthesize the observations and theories and provide information for areas where data do not exist at a given time based on simulations that were calibrated with existing data. Thus, they provide a wealth of information for any time during the model simulation period and for any location within the model domain. Most importantly, hydrodynamic models can forecast future conditions and analyze scenarios of change due to either climate or anthropogenic influences, such as sea level changes; coastal inundation and flooding; or the construction or removal of a river dam, a sewage outfall, or an ocean inlet. A local example is using the FKEYS-HYCOM to predict changes in circulation around Florida Bay and the Florida Keys associated with the Comprehensive Everglades Restoration Plan.



Models use grids and color for analyzing and illustrating ocean conditions, such as this FKEYS-HYCOM model domain and bathymetry map. Color scale shows depths in meters. White areas are less than 50 meters (164 feet) deep; purple color indicates the deepest areas in the Florida Straits. Rectangles depict the model gridding, where each box is actually divided into 10 more boxes in the model grid.

Model grid map prepared by H.S. Kang - UM/RSMAS.

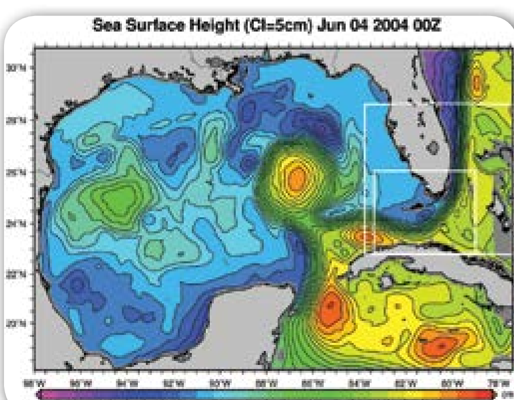
How are models created?

First, the modelers select the model domain, which covers the area of interest. Then the domain is divided into small gridded areas. The selected grid size depends on the phenomena modelers want to study and on the computer resources available to process all the data in the model and solve the equations of motion on every model grid. The coastal domains require smaller grids, and the smaller the grid, the greater the number of cells for a given study area and the more expensive it is to run the model, because it requires more computer power. The FKEYS-HYCOM has a high resolution (very small) rectangular grid of about a half mile in each direction. The model domain is large, and it has a total of 437 by 361 boxes, which is quite a lot when solving a very complex code every few minutes for years of simulation and at many different depths in the water column. For instance, the FKEYS-HYCOM model has 26 vertical layers. High performance computing resources (supercomputers) are required, and lots of storage space (many terabytes) is necessary to archive the results. Each grid box is given information about the latitude and longitude; the depth; and the forcing functions, such as wind, heating/cooling, evaporation, and precipitation. These forces change over time, creating different circulation patterns. In addition, grids near the land might receive river runoff, whereas grids near the model boundaries require information on currents and water properties (e.g., temperature, salinity) from larger-scale models.

Models connect circulation around the Florida Keys with the ocean currents

The FKEYS-HYCOM model is nested (embedded) in a hierarchy of larger-scale models, such as South Florida, the Gulf of Mexico, and the full North Atlantic Ocean, which, in itself, is embedded in a global model that covers the entire worldwide oceans. This particular modeling system is based on code used in the HYCOM model (hycom.org); other modeling systems use a different code. The larger-scale models are coarser (i.e., lower resolution or larger grid cells, which means less detail in topography), going up to several kilometers at each side of their grid. Using this downscaling approach, simulations with the FKEYS-HYCOM properly represent coastal flows and their interaction with the neighboring and remote oceanic currents.

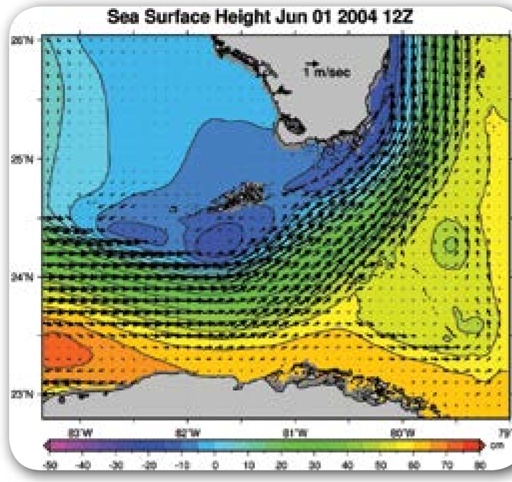
An example of modeling, shown in the figures, illustrates the influence of eddies along the Florida Keys. Sea surface height was mapped by the Gulf of Mexico-HYCOM model for June 4, 2004. The Loop Current-Florida Current system is a dominant circulation feature as the continuation of the Caribbean Current that enters at Yucatán. Many cyclonic and anticyclonic eddies fill the Gulf of Mexico domain and enter the Florida Straits. The same features are present in the embedded FKEYS-HYCOM model, but many more details can be revealed, especially near and around the Keys, because this model has higher resolution that allows for more topographic details. An eddy was observed as a rounded feature off the Lower Keys on June 1, 2004. This eddy became an elongated feature by June 10, 2004, as the Florida Current meandered closer to the Keys. These are favorable conditions for eddy breakup, which results in delivery of nutrients and larvae from upstream spawning grounds. Note that there are times that the Loop Current is extended all the way to the northern Gulf of Mexico



Model grid map prepared by H.S. Kang - UM/RSMAS.

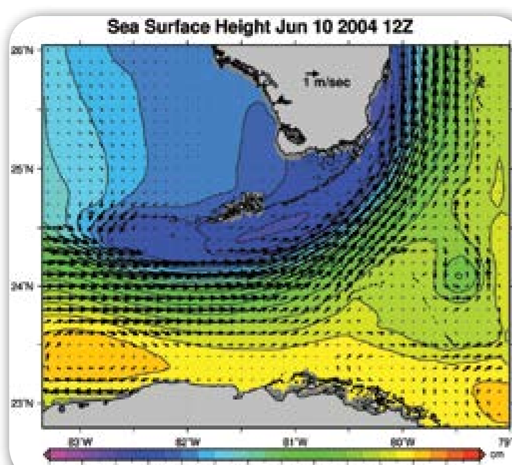
Sea surface height for the Gulf of Mexico-HYCOM model on June 4, 2004. Color scale gives sea surface height in centimeters. High values (red and green) show the oceanic current system and clockwise eddies. Blue-colored eddies rotate counterclockwise. The white boxes mark the domains of the embedded south Florida-HYCOM (large box) and FKEYS-HYCOM (small box) models. Model fields provided by Pat Hogan and Ole-Martin Smedstad, Naval Research Laboratory, Stennis Space Center.

and can interact with the Mississippi River, potentially carrying agricultural runoff from the midwestern United States all the way to the Florida Keys.



Model grid map prepared by H.S. Kang - UM/RSMAS.

Sea surface height map for the FKEYS-HYCOM model on June 1, 2004. Color scale gives sea surface height in centimeters. High values (red, orange, and green) show the oceanic current system and clockwise eddies. The blue-colored eddies rotate counterclockwise. Black arrows show the strongest currents (greater than 50 cm/s) along the Florida Current and around the eddies. Note the large, circular eddy (dark blue) off the Lower Keys.



Model grid map prepared by H.S. Kang - UM/RSMAS.

Sea surface height map for the FKEYS-HYCOM model on June 10, 2004. Color scale gives sea surface height in centimeters. High values (orange and green) show the oceanic current system and clockwise eddies. Blue colored eddies rotate counterclockwise. Black arrows show the strongest currents (greater than 50 cm/s) along the Florida Current and around eddies. Note how the eddy off the Lower Keys (dark blue) has elongated, a favorable condition for eddy breakup and delivery of nutrients and larvae from upstream sources.

A hydrodynamic and mass transport model has been developed for Biscayne Bay

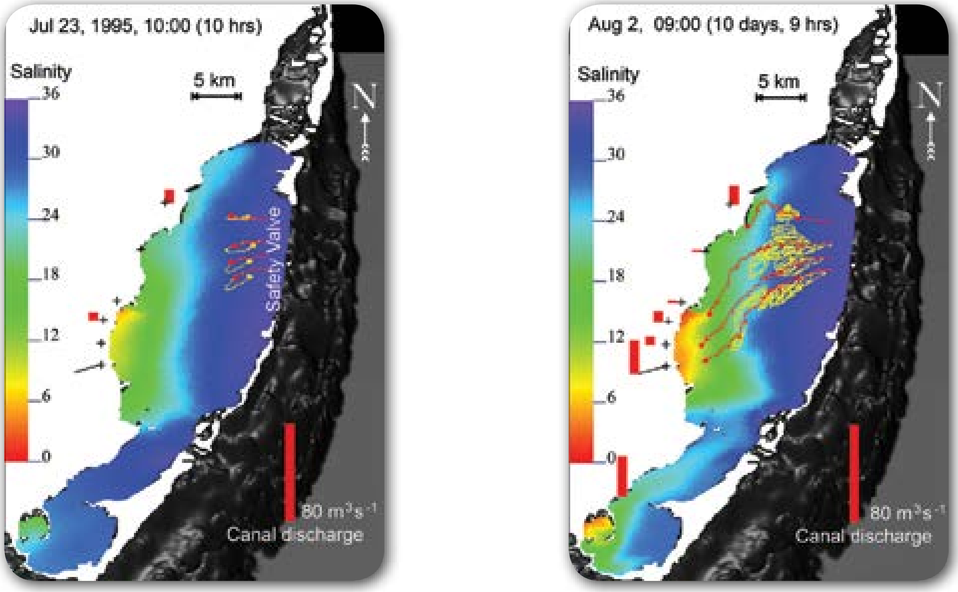
John D. Wang

A hydrodynamic and mass transport model is a predictive tool used to forecast or hindcast circulation patterns and transport of materials in a waterbody. Such information is useful to a broad range of potential users, such as sailors, pollution control managers, ecologists, and public health officials. All of these users may need knowledge of the water current velocities, water surface fluctuations, and transport of materials dissolved or suspended in the water. Supported by observations in the field that are limited by the cost, effort, and time required to collect them, a hydrodynamic numerical model can provide predictive information on spatial and temporal patterns on which informed decisions can be made.

For example, competitive sailors are interested in water currents as forced by tides and wind to gain an advantage over other sailors. Substantial changes in both magnitude and direction of currents occur throughout south Biscayne Bay and could be used advantageously to plan a sailing route. The model used to calculate this information is a finite element numerical model that expresses fundamental physical principles in a step by step fashion that are then used to calculate water current velocities and water surface fluctuations.

Adding a mass transport module to the hydrodynamic model allows the investigation of the pathways and travel times of substances in the water, such as fish larvae, polluted water discharged from the canals distributed along the western edge of the Bay, or microbes that are introduced into the water point and nonpoint sources.

The model also can simulate paths of fish larvae that arrive at the eastern opening of the Bay and are subsequently transported into the Bay toward suitable nursery grounds by surface currents.



Model simulation of dispersal of fish larvae that arrive at the eastern opening of the Biscayne Bay (Safety Valve). The model predicts paths of larvae without swimming behavior (yellow) and with swimming behavior (red) 10 hours (left) and 10.4 days (right) after time of arrival at the eastern opening of the Bay. The effect of canal discharge (red bars) on salinity of the Bay is also shown.

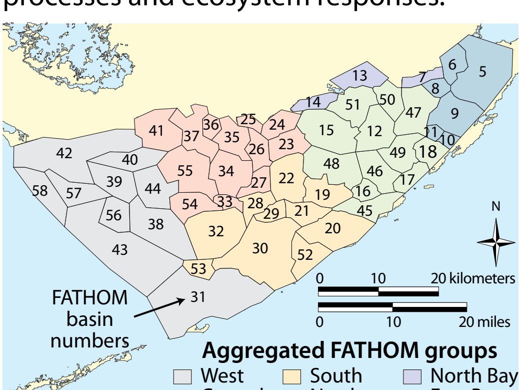
Hydrologic models predict salinity in Florida Bay

Frank E. Marshall and William K. Nuttle

Salinity and its pattern of variation define estuarine and coastal ecosystems. Salinity is a major factor in determining the types of plants and animals present and where they live. Salinity varies spatially and over time in response to fluctuations in the quantity and location of freshwater inflows. Models are capable of predicting how salinity changes and allow water managers to evaluate different ways of delivering freshwater to Florida Bay as part of the Comprehensive Everglades Restoration Plan.

Two general approaches have been used for constructing salinity models of Florida Bay. The first is empirical and relies on accurately describing observed salinity variations. The second is mechanistic and depends on accurately accounting for the physical processes (e.g., flow rates, tidal exchange, evaporation) that drive changes in salinity. In both approaches, the accuracy of the forecasts is limited by the data available for describing patterns of salinity variation and the ability to quantify the driving processes.

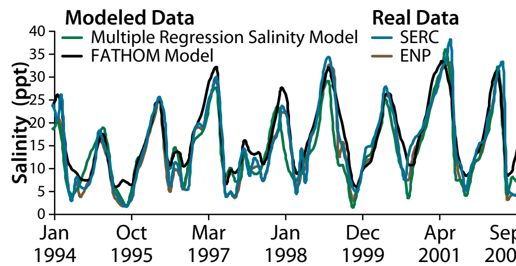
The empirical approach is simpler, using descriptive analyses to formulate models that confirm statistical relationships. Regression models are a method to explain the relationships between driving processes and ecosystem responses.



Map identifying Florida Bay basins and the aggregated regions used in FATHOM for salinity calculations.

A Multiple Regression Salinity Model has been developed for Florida Bay to evaluate freshwater delivery alternatives and for paleoecological investigations.

Mechanistic salinity models are mass balance models that provide a comparison of the inputs and outputs



A comparison of observed salinity data (real data) from Everglades National Park (ENP) and Southeast Environmental Research Center (SERC) and forecasts made by Multiple Regression Salinity Model and Fathom Salinity Models (FATHOM) in Long Sound. Results show that models accurately predict salinity variations used to guide water management decisions to restore natural freshwater inflows and salinity to Florida Bay.

of water and salt between basins. Mass balance models can be simple (box) models or more complex hydraulic and hydrodynamic models. FATHOM is a hydraulic model that accurately accounts for the exchanges between water and salt in basins delineated by geographic features (mud banks) in Florida Bay in a manner similar to creek flow. By design, hydrodynamic models are intended for more detailed and spatially discrete applications because of the effort and high cost to run large-scale hydrodynamic models for regional scenarios.

To date, the most widely used models for developing historical re-creations and simulating future salinity regimes for evaluating water management alternatives are the FATHOM hydraulic model and the Multiple Regression Salinity Model. These models have proven useful for planning-level decisions on a regional basis.

Sea surface temperature can be used to predict coral bleaching events

Lewis J. Gramer and James C. Hendee

Coral bleaching is the loss of color in corals due to stress-induced expulsion of unicellular algae (i.e., zooxanthellae) that live within coral tissues. Zooxanthellae give corals their particular color, and under stress those cells are expelled, leading to a lighter or completely white appearance in corals.

High sea surface temperature along with high incident radiation are the primary causes of summer coral bleaching. Because reef-building corals live near their upper thermal tolerance limits, small increases in the temperature of the ocean over several weeks, or a large increase over a few days, can cause bleaching events and ultimately may lead to coral death.

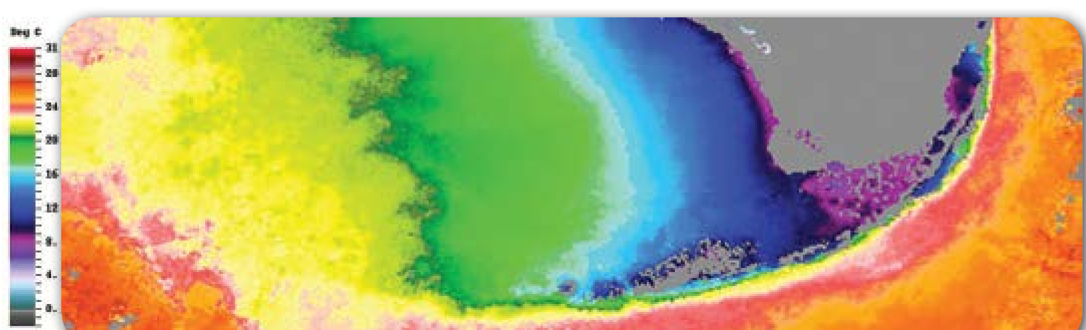
The ability to provide advanced warning of possible major coral bleaching events is important in sustaining healthy reefs. When coral reef managers and stakeholders are alerted to potential bleaching events, they can mobilize monitoring efforts, implement response strategies, and educate reef users and the general public on coral bleaching and the possible effects on the reef ecosystem.

The National Oceanic and Atmospheric Administration (NOAA) has partnered with researchers at the University of South Florida to develop a system for forecasting potential coral bleaching events. The NOAA Integrated Coral Observing Network system uses data (e.g., sea temperature, winds, light penetration) from local lighthouse stations and satellites to alert managers and scientists of the risk of coral bleaching. The forecasting system takes a page from artificial intelligence research, using a program called an expert system to model the way coral reefs respond to environmental extremes. As sea temperature extremes become more frequent and other stressors like pollution and other human activities affect coral reefs, forecasting coral bleaching becomes even more critical to managers. The goal of NOAA is to issue bleaching forecasts for coral reefs worldwide based on global high resolution satellite data.

Coral bleaching

Coral bleaching can be induced by:

- Increased or reduced water temperature;
- Increased solar radiation;
- Changes in water chemistry;
- Changes in local water circulation;
- Sedimentation; and
- Pathogenic infections.



C. Hu - USF

Satellite sea surface temperature composite for January 8 – 14, 2010, when extreme cold sea temperatures in shallow nearshore waters of the Florida Keys (blue color immediately adjacent to the Atlantic side of the Florida Keys) caused significant bleaching and mortality of corals. This image shows that reefs separated from one and another by only a few miles may experience very different temperatures.

Oceanic processes affect south Florida coral reefs

James J. Leichter

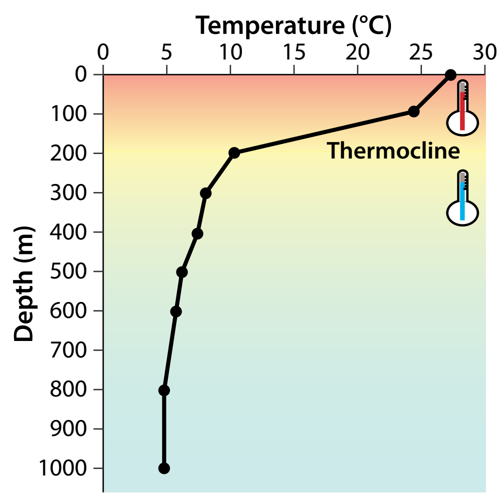
The oceanic environment plays a central role in shaping the biological communities of south Florida and the Florida Keys. A dominant feature of the system is the presence of strong and highly variable currents. The extensive flushing of water through the system is believed to contribute to high productivity and high rates of fish and invertebrate recruitment.

Close to shore (within a few kilometers of the shoreline), winds and tides drive circulation and exchange of water with inshore regions. The effects of freshwater runoff associated with strong rains and the tidal exchange of water from Florida Bay can be significant in the Florida Keys Atlantic Coastal Zone.

Further offshore, oceanic currents sweep over the shallow bank reefs and provide an oceanic influence and rapid alongshore transport of dissolved and suspended materials. The central axis of the Florida Current that sweeps past the Florida Keys and Atlantic coast of south Florida typically lies anywhere from 10 – 70 kilometers (6 – 43 miles) offshore because of the strongly meandering nature of the flow. Numerous eddies embedded in the northward flow can result in local reversals of the direction of the alongshore flow, lasting one to several days, and have been shown to be locally important in providing pulses of animal larvae arriving on shallow reefs. The total volume transported by the Florida Current varies seasonally (strongest in spring/summer) and interannually.

Other important features of the oceanic environment that strongly influence the reefs of south Florida and the Florida Keys are the vertical stratification of water column temperature and density and subsurface internal waves. A typical vertical profile of the offshore water column shows warm surface temperatures separated from significantly cooler deeper waters by a region of rapid change in temperature with depth called a "thermocline." This thermocline typically is observed at depths of 50 – 80 meters (164 – 262 feet) in the Florida Keys.

The combination of vertical stratification, strong currents, and topographic features of the Florida Straits produces numerous internal waves at tidal and faster frequencies. Internal waves are vertical oscillations of the thermocline with amplitudes of up to tens of meters. These subsurface phenomena have a surface manifestation of parallel "slicks" separated by roughly 100 – 200 m (328 – 656 ft) and propagate toward shore. The slicks often contain surface concentrations of seaweeds and debris.

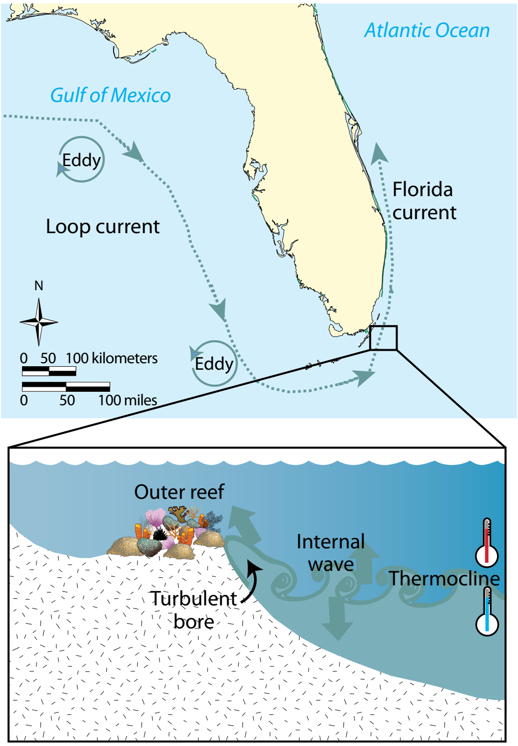


A thermocline is an area where the temperature changes rapidly with depth. Note the rapid change in temperature between approximately 50 – 150 m (165 – 500 ft). A thermocline causes vertical stratification of the water column, which means that it takes energy to mix the water from top to bottom.

When internal waves travel into shallow water, typically at depths of 10 – 30 m (33 – 98 ft) along the reef margin in the Florida Keys, they can strongly affect the temperatures and nutrient concentrations through upwelling of cold, nutrient-rich deep water. Temperature fluctuations as large as 5° – 8° C (9° – 14° F) on time frames ranging from minutes to a few hours are common along the entire region, especially during May – September. Drops in temperature are accompanied by marked increases in concentrations of dissolved inorganic nutrients and suspended particles. The upwelled water is rich in nutrients because of natural processes. When plankton and other organisms produced or living in surface waters die, they often sink toward the bottom. As these materials sink, they break down and get eaten and excreted, and the end result is the slow and continuous addition of nitrogen and phosphorus to waters with increasing depth.

Upwelled water flows onto the reef more often than people realize, sometimes several times a day. Although the biological effects of upwelling along the reef tract are not well understood, the presence of this cold, nutrient-rich water on the reef for extended periods of time has the potential to cause significant affects on ecological structure and biodiversity of the south Florida coral reef community. One indication of the prevalence of nutrient upwelling is widely distributed communities of large, densely packed macroalgae (seaweeds) observed at depths of 40 – 60 m (130 – 200 ft) on the slopes seaward of the bank reefs of the Florida Keys.

Strong bouts of internal tidal upwelling can deliver as much as 20 – 40 times more nitrogen and phosphorus to the outer reef tract than estimates of land-based nutrient pollution from sewage and stormwater runoff. However, this finding does not contradict that there are nearshore pollution problems in south Florida or that there is a need to better understand the dynamics of nearshore pollutants making their way offshore. Also, there are significant periods between upwellings and long periods in each year, particularly in October – December, when internal tidal upwelling is minimal. It is possible that



Internal tidal bores deliver cool, nutrient-rich water from the ocean depths to the outer reefs of the Florida Keys.

anthropogenic nutrient inputs may cause subtle alterations in baseline nutrient concentrations and shifts toward a more continuous, chronic nutrient availability in a system that is naturally characterized by large, but highly episodic inputs.

Global warming of surface waters may lead to increased water column stratification. A possible effect of increased stratification is an increase in the number of internal bores reaching Florida reef slopes and significant increases in reef slope nutrient availability. Another possible effect of climate change is a deepening of the surface mixed layer, which might result in internal bores occurring deeper on the reef slopes with reduced nutrient delivery into shallower water. Although the impacts of humans on the marine environments of south Florida are dramatic and complex, it is important to accurately assess effects of natural processes on the ecosystem.

Introduction citations

1. Lee TN, Williams E. 1999. Mean distribution and seasonal variability of coastal currents and temperature in the Florida Keys with implications for larval recruitment. Bull Mar Sci. 64: 35-56. *Larval and adult sea life are brought to the Keys by ocean currents.*
2. Leichter JJ, Stewart HL, Miller SL. 2003. Episodic nutrient transport to Florida coral reefs. Limnol Oceanogr. 48: 1394-1407. *Upwelling of deep ocean water is a source of nutrients to offshore coral reefs.*
3. Spalding M, Ravlious C, Green EP. 2001. World Atlas of Coral Reefs. UNEP World Conservation and Monitoring Center, London, 428 pp. *Causeways in the Florida Keys disrupt flow from Gulf of Mexico to the Atlantic Ocean.*
4. Wikipedia. 2011. Oceanography. Available from: http://en.wikipedia.org/wiki/Oceanography (Updated 11 Feb 2011; cited 11 Feb 2011). *History of oceanography.*
5. Dive and Discovery. 2005. History of Oceanography: The Challenger Expedition. Available from: http://www.divediscover.whoi.edu/history-ocean/challenger.html (Cited 11 Feb 2011). *History of oceanography, Challenger Expedition.*
6. Harvard University Library Open Collection Program: Expeditions and Discoveries. 2011. Pacific Expeditions of the U.S. Commission Steamer *Albatross*, 1891, 1899-1900, 1904-1905. Available from: http://ocp.hul.harvard.edu/expeditions/albatross.html (Cited 11 Feb 2011). *History of three expeditions of the* Albatross.
7. MEER. University of California Online Course in Marine Biology. A brief history of marine biology and oceanography. Available from: http:www.meer.org/ebook/mbhist.htm (Cited 11 Feb 2011). *A summary of major oceanographic events and a chronology of people, events, and expeditions.*
8. Florida Institute of Oceanography. Who We Are. 2010. Available from: http://fio.usf.edu/WhoWeAre.aspx (Cited 11 Feb 2011). *Background and goals of the Florida Institute of Oceanography.*
9. National Oceanic and Atmospheric Administration, Office of Coast Survey. How hydrodynamic models are used. Available from: http://www.nauticalcharts.noaa.gov/csdl/learn_models.html (Cited 11 Feb 2011). *A primer on understanding ecological modeling.*
10. Fajans J. 2007. SEAKEYS C-Man stations record real-time conditions. Sounding Line, Winter 2007-Spring 2008. Available from: http://floridakeys.noaa.gov/edu/soundingline/SEAKEYS.pdf (Cited 11 Feb 2011). *History and use of fixed oceanographic platforms to record real-time sea conditions for Sustained Ecological Research Related to the Management of the Florida Keys Seascape.*

Further reading

Andrews JC, Gentien P. 1982. Upwelling as a source of nutrients for the Great Barrier Reef ecosystem: A solution to Darwin's question? Mar Ecol Prog Ser. 8: 257-269. *Nutrients are delivered to the living coral of reefs by localized upwelling events.*

Boyer JN, Jones RD. 2002. A view from the bridge: External and internal forces affecting the ambient water quality of the Florida Keys National Marine Sanctuary. In: Porter, J.W. and K.G. Porter (eds.) The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An ecosystem sourcebook. Boca Raton, FL: CRC Press. p. 609-628. *Water quality of the Lower Keys and Marquesas is most influenced by the southwest Florida Shelf; the Middle Keys by southwest Florida Shelf and Florida Bay transport; the backcountry by internal nutrient sources; and the Upper Keys by intrusions of the Florida Current.*

Fratantoni PS, Lee TN, Podesta G, Muller-Karger F. 1998. The influence of Loop Current perturbations on the formation and evolution of Tortugas eddies in the southern Straits of Florida. J Geophys Res. 103: 24759-24779. *There is a strong relationship between the generation of anticyclonic rings from the Gulf of Mexico Loop Current and the evolution of Tortugas eddies within the southern Straits of Florida.*

Gibson RN. 2003. Go with the flow: tidal migration in marine animals. Hydrobiologia 503: 153-161. *Some animals use tidal currents selectively for transport to new habitats.*

Henry JA, Portier KM, Coyne JC. 1994. The climate and weather of Florida. Pineapple Press, Sarasota, FL. 27 pp. *Interesting facts about Florida's unique climate and weather.*

Hu C, Nelson J, Johns E, Chen Z, Weisberg R, Muller-Karger FE. 2005. Mississippi River Water in the Florida Staits and in the Gulf Stream off Georgia in Summer 2004. Geophys Res Lett 32:L14606. *Floodwater discharge from the Mississippi River was tracked to south Florida and Georgia.*

Hughes T, Szmant AM, Stenbeck R, Carpenter R, Miller S. 1999. Algal blooms on coral reefs: What are the causes? Linmol Oceanogr. 44: 1583-1586. *A critque of Lapointe (1997) opining that his data do not support a uniform threshold for eutrophication on coral reefs and that declining herbivory plays a major role in macroalgal abundance.*

Kelble CR, Johns EM, Nuttle WK, Lee TN, Smith RH, Ortner PB. 2006. Salinity patterns of Florida Bay. Estuar Coast Shelf Sci. 71: 318-334. *The salinity of Florida Bay has undergone dramatic changes over the past century. Salinity values reached their most extreme, up to 70 ppt, in the late 1980s, concurrent with ecological changes in Florida Bay including a mass seagrass die-off.*

Lapointe BE. 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnol Oceanogr. 42: 1119-1131. *Bottom-up nutrient enrichment is a causal factor of a phase shift toward macroalgae on reefs of Jamaica and southeast Florida.*

Lapointe BE, Smith NP. 1987. A preliminary investigation of upwelling as a source of nutrients to Looe Key National Marine Sanctuary. NOAA Technical Memorandum NOS MEMD 9. Washington, D.C. *Upwelling that occurs during spring and summer at Looe Key may be related to seasonal changes in volume transport of the Florida Current and the seasonal appearance of the Pourtales counter current.*

Lee TN. 1975. Florida current spin-off eddies. Deep-Sea Res. 22: 753-763. *Near-surface current meter records from the narrow coastal zone inside the Florida Current off Boca Raton and Pompano, Florida shows the occurrence of a large number of cyclonic current reversals that are not wind or tide induced.*

Lee TN, Johns E, Melo N, Smith RH, Ortner P, Smith D. 2006. On Florida Bay hypersalinity and water exchange. Bull Mar Sci. 79: 301-327. *Hypersalinity in Florida Bay is caused by the combination of reduced freshwater inputs during the dry season combined with weak basin water renewal rates. Hypersalinity development could be greatly reduced by diversion of freshwater to McCormick Creek during dry seasons.*

Lee TN, Mayer DA. 1977. Low-frequency current variability and spin-off eddies on the shelf off southeast Florida. J Mar Res. 35: 193-220. *A description of the formation of eddies off the Florida Current along the south Florida shelf.*

Lee TN, Melo N, Johns E, Kelble C, Smith RH, Ortner P. 2008. On water renewal and salinity variability in the northeast subregion of Florida Bay. Bull Mar Sci. 82: 83-105. *The northeast subregion of Florida Bay receives approximately 75% of the direct freshwater runoff to the bay, most of which is retained within the subregion* *and has little impact on the dilution of hypersalinity development in adjacent subregions. Groundwater inflows to Florida Bay are negligible and probably not a factor in water quality considerations.*

Lee TN, Smith NP. 2002. Volume transport variability through the Florida Keys tidal channels. Cont Shelf Res. 22: 1361-1377. *Most wind directions cause a slope of sea level and Gulf to Atlantic outflow toward the reef tract. Minimum outflow occurs in the fall when winds toward the southwest and west are more frequent and inflows to Florida Bay can persist for several days.*

Lee TN, Williams E. 1999. Mean distribution and seasonal variability of coastal currents and temperature in the Florida Keys with implications for larval recruitment. Bull Mar Sci. 64: 35-56. *Larval and adult sea life are brought to the Keys by ocean currents.*

Lee TN, Williams E, Wilson D, Johns E, Smith N. 2002. Transport processes linking south Florida coastal ecosystems. In: Porter JW, Porter KG (eds.). The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An ecosystem sourcebook. CRC Press, Boca Raton, FL. p. 309-342. *Eddies and coastal countercurrents provide opportunities for larval recruitment from both local and foreign sources.*

Lee TN, Yoder JA, Atkinson LP. 1991. Gulf Stream frontal eddy influence on productivity of the southeast U.S. Continental Shelf. J Geophys Res. 96: 22,191-22,205. *Weekly period meanders and eddies are persistent features of the Gulf Stream frontal dynamics from Miami, Florida to Cape Hatteras, North Carolina.*

Leichter JJ, Stewart HL, Miller SL. 2003. Episodic nutrient transport to Florida coral reefs. Limnol Oceanogr. 48:1394-1407. *Documents nutrient fluxes associated with internal tidal bores on coral reefs in the Florida Keys (Conch Reef).*

Mitchum GT, Sturges W. 1982. Wind driven currents on the West Florida Shelf. J Phys Oceanogr. 12: 1310-1317. *Currents and sea level are coherent with alongshore wind stress and lag it by approximately half a day. Little coherence is found with cross-shelf wind stress.*

Nuttle WK, Fourqurean J, Cosby B, Zieman JC, Robblee MB. 2000. The influence of new freshwater supply on salinity in Florida Bay. Water Resour. 36: 1805-1822. *Modeling shows that increased runoff will lower salinity in Eastern Florida Bay, increase the variability of salinity in the southern part of the bay, and have little effect in central and western regions.*

Palumbi S, Warner R, Roberts C. 2003. The science of larval dispersal and its implications for marine reserve planning. MPA News 4(9): 1-4. Available from: http://depts.washington.edu/mpanews/MPA40.htm (Cited 11 Feb 2011). *Larvae may play a relatively active role in determining their own settlement area. Some larvae may even resist currents in order to stay in local waters, the home range of their parents, establishing a cycle of self-recruitment for the resident population.*

Rudnick DL, Davis RE, Eriksen CC, Frantantoni DM, Perry MJ. 2004. Underwater gliders for ocean research. Mar Technol Soc J. 38: 48-59. *Underwater gliders are a new technology in active development for oceanographic observations. A variety of sensors have been deployed on gliders, and many more are in the process of being integrated.*

Smith NP. 1994. Long-term Gulf-to-Atlantic transport through tidal channels in the Florida Keys. Bull Mar Sci. 54: 602-609. *The long-term net flow is consistently out of the Gulf of Mexico toward the Atlantic Ocean.*

Wang JD, van de Kreeke J, Krishman N, Smith D. 1994. Wind and tide responses in Florida Bay. Bull Mar Sci. 54: 579-601. *Numerical model simulation shows that tides are strongly influenced by a combination of bottom friction and obstruction to flow from chained islands and submerged banks in Florida Bay.*

Wang JD, Luo J, Ault JS. 2003. Flows, salinity and some implications on larval transport in south Biscayne Bay, Florida. Bull Mar Sci. 72(3): 695-723. *A numerical model was developed to describe the currents, residence times, salinity patterns, and larval transport in Biscayne Bay.*

Website references

Euphrates. Web Page Community at William Patterson University. Oceanography. Available from: http://euphrates.wpunj.edu/faculty/pardir/Courses/Oceanography/Notes/ocean_sections.htm (Accessed 14 Feb 2011). *A lecture on collecting oceanographic data.*

Gyory J, Mariano AJ, Ryan EH. 2001-2008. The Gulf Stream. University of Miami Cooperative Institute for Marine and Atmospheric Studies. Surface Currents in the Atlantic Ocean. Available from: http://oceancurrents.rsmas.miami.edu/atlantic/gulf-stream.html (Accessed 14 Feb 2011). *Summary of the Gulf Stream Current.*

Gyory J, Rowe E, Mariano AJ, Ryan EH. 2001-2008. The Florida Current. University of Miami Cooperative Institute for Marine and Atmospheric Studies. Surface Currents in the Atlantic Ocean. Available from: http://oceancurrents.rsmas.miami.edu/atlantic/florida.html (Accessed 14 Feb 2011). *The Florida Current receives water from the Loop Current and the Antilles Current.*

Hu C. Parent Directory Index. Available from: http://optics.marine.usf.edu/~hu/Public/keys/ (Accessed 07 Jul 2011). *A catalog of satellite images of the Florida Keys.*

MacKenzie D. 2002. Vertical migration of zooplankton: a biphasic feeding strategy that enhances new production? Available from: http://www.fisherycrisis.com/copepods.htm (Accessed 14 Feb 2011). *A summary of the feeding ecology of zooplankton in the open ocean, rising to surface at dusk and descending at dawn.*

National Aeronautics and Space Administration, Earth Observatory. Mississippi River escapes the Gulf. Available from: http://earthobservatory.nasa.gov/IOTD/view.php?id=5868 (Updated 11 Mar 2009; accessed 14 Feb 2011). *Mississippi River plume in July-September 2004 did not mix with the surrounding sea water immediately. Instead, it stayed intact as it flowed through the Gulf of Mexico, into the Straits of Florida, and entered the Gulf Stream.*

National Hurricane Center. Tracks of 2004 hurricanes. Available from: http://www.nhc.noaa.gov/tracks/2004atl.gif (Accessed 14 Feb 2011). *Tracks of Atlantic hurricanes in 2004.*

National Oceanic and Atmospheric Administration. Coral Health and Monitoring Program. Available from: http://www.coral.noaa.gov (Updated 14 Feb 2011; accessed 14 Feb 2011). *The NOAA Coral Health and Monitoring Program (CHAMP), based at NOAA's Atlantic Oceanographic and Meteorological Laboratory in Miami, gathers physical and geochemical data from reefs world-wide and develops assessment expert systems and other research, with the help of NOAA's Coral Reef Conservation Program and other funding.*

National Oceanic and Atmospheric Administration. Integrated Coral Observing Network. Available from: http://ecoforecast.coral.noaa.gov (Accessed 14 Feb 2011). *A NOAA CHAMP Web site specifically providing ecological forecasts of coral bleaching, spawning, blooms, and other changes in reef waters worldwide.*

National Oceanic and Atmospheric Administration. New NOAA Coral Bleaching Prediction System. Available from: http://www.noaanews.noaa.gov/stories2008/20080710_coralbleaching.html (Accessed 14 Feb 2011). *Description of coral bleaching prediction system based upon sea surface temperature.*

National Oceanic and Atmospheric Administration. How hydrodynamic models are used. Available from: http://www.nauticalcharts.noaa.gov/csdl/learn_ models.html (Accessed 14 Feb 2011). *A primer on the development and use of hydrodynamic models.*

National Oceanic and Atmospheric Administration and the University of North Carolina at Wilmington. 2011. Aquarius Reef Base. Available from: http://www.uncw.edu/aquarius/ (Accessed 14 Feb 2011). *A description and use of the world's only underseas research station, owned by NOAA and operated out of Key Largo, FL by the University of North Carolina at Wilmington.*

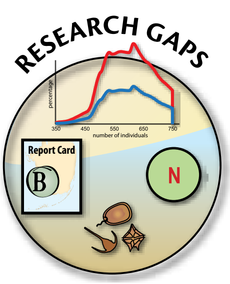
Wang JD, Swain ED, Wolfert M A, Langevin CD, James DE, Telis PA. 2007. Applications of Flow and Transport in a Linked Overland/Aquifer Density Dependent System (FTLOADDS) to Simulate Flow, Salinity, and Surface-Water Stage in the Southern Everglades, Florida. U.S. Geological Survey Scientific Investigations Report 2007-5010, 112 p. Available from: http://pubs.usgs.gov/sir/2007/5010/(Updated: 18 Oct 2007; cited 11 Feb. 2011). *Modeling shows agreement between measured and simulated total flows to Florida Bay and coastal salinities.*

Wikipedia. Challenger Expedition. Available from: http://en.wikipedia.org/wiki/Challenger_expedition (Updated 8 Jan 2011; accessed 14 Feb 2011). *A summary of the HMS Challenger Expedition, 1872-1876.*

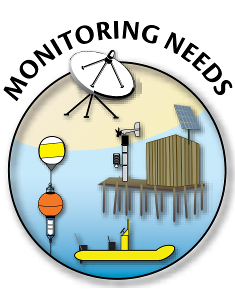
3. WATER QUALITY

Water Quality
Chapter Recommendations

- Design management plans and actions to **address local priorities** with an awareness of potential impacts to other portions of the ecosystem.
- Support scientific research and monitoring to provide critical and current information required for effective **adaptive management**.
- Recognize that the ecosystem is affected by events that can not be effectively managed at a local scale, but that does not preclude taking action on stressors that can be controlled through sound, **local management strategies**.



- Establish **nutrient thresholds** and biocriteria to provide a scientific base for water quality standards.
- Quantify the effects of **nutrient and freshwater loading** on the species composition of phytoplankton and the effects of changes in species composition on the food web.
- Investigate distribution, concentration, and effects of **pharmaceuticals** discharged in wastewater on aquatic organisms.
- Assess the role of **human viruses and bacteria** on water quality, public health, and ecosystem functions.



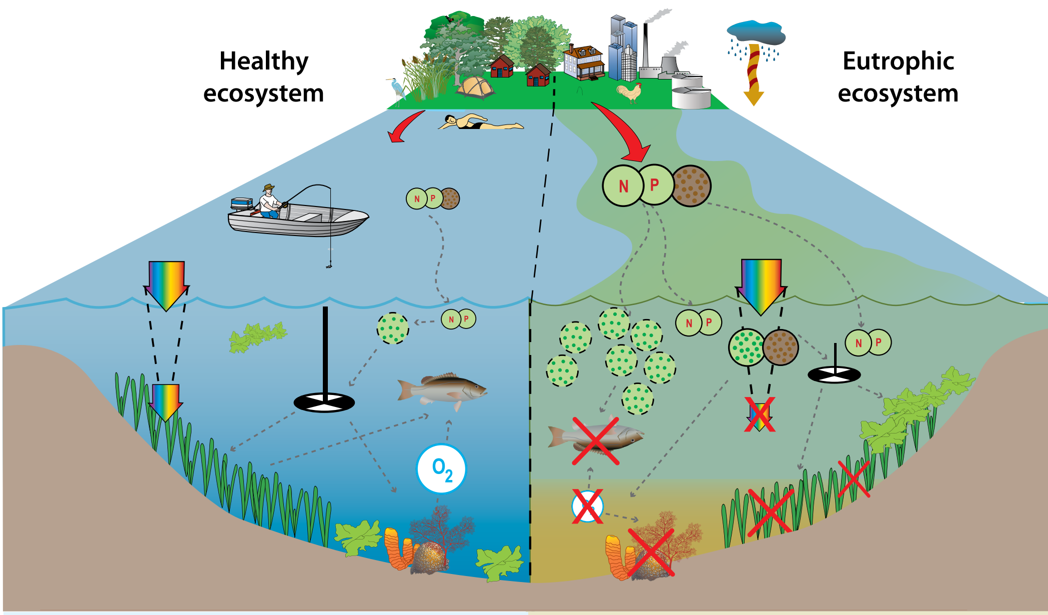
- Continue to conduct current **broad-scale water quality monitoring** to provide information on the status and trends of the ecosystem and long-term correlative data for physical and biological observations, and to help pinpoint sources of degradation to the water quality of south Florida.
- Implement monitoring programs on a sufficient scale to assess the effects of **improvements due to wastewater and stormwater infrastructure**.
- Advance tools for broad-scale monitoring to provide early warning of pollutants or **harmful algal blooms**.
- Integrate *in situ* and remote monitoring to allow rapid response to events, such as accidents, storms, or other **episodic events**.

Chapter title page: Water reflections. M. Stone, Mac Stone Photography.

Introduction

What is water quality?

"Water quality" is a term that summarizes the physical, chemical, and biological characteristics of a body of water.[1] The concept of what constitutes "good" water quality is based on several interrelated parameters, including how the water will be used (e.g., drinking, swimming, fishing); concentrations of materials in the water above natural background levels that could be deleterious to humans, plants, or animals (pollution); and the presence of compounds not usually found in the water (contaminants).[2] Section 304(a)(1) of the Clean Water Act requires the United States Environmental Protection Agency (EPA) to develop criteria for water quality that accurately reflect the latest scientific knowledge and protect the designated use.[3] The Clean Water Act and the Water Quality Standards



In healthy aquatic ecosystems, input of nutrients including nitrogen and phosphorus allow for the balanced growth of seagrasses and macroalgae (submerged aquatic vegetation), and phytoplankton (chlorophyll *a*). A low level of chlorophyll *a* in the water column helps keep water clarity high, allowing light to penetrate deep enough to reach submerged aquatic vegetation. Primary productivity by submerged aquatic vegetation and phytoplankton results in dissolved oxygen levels suitable for healthy fish and benthic communities and allows humans to enjoy the benefits of a healthy coastal environment.

In an eutrophic aquatic ecosystem, increased nutrient and sediment loads from land-based sources, including wastewater, agriculture, and stormwater, as well as nutrients dissolved in rainwater, can trigger blooms of phytoplankton and macroalgae. These blooms can result in decreased water clarity, decreased light penetration, decreased dissolved oxygen, loss of seagrasses, nuisance/toxic algal blooms, and the contamination or die-off of fish and benthic communities.

Adapted from Bricker et al. 2007.

Water Quality

Handbook (EPA-823-B-94-005) (epa.gov/waterscience/standards/handbook/) provide guidance to states and tribes in adopting water quality standards that must be reviewed and approved by the EPA.[4] There are three components to the water quality standards: 1) the designated use; 2) the criteria to protect that use; and 3) an antidegradation policy. Water quality criteria establish acceptable limits for materials found in water. The State of Florida water quality standards are found in Chapter 62-302 of the Florida Administrative Code.

Definitions of environmental water quality standards are based on conditions that may result in a change in the quantity or health of organisms that live in the water. However, because even pristine natural ecosystems undergo changes in response to natural variations and ecosystems gradually change over time (i.e., ecological succession), it is difficult to determine the exact point (i.e., threshold) that changes in water quality parameters begin to cause degradation of the ecosystem. In response to that problem, some states have adopted nonnumeric or narrative water quality criteria that use changes in biological communities to assess whether pollutants have reached concentrations that result in unacceptable changes to the natural ecosystem.[5] Two numeric water quality criteria are currently in place for marine waters of south Florida: a dissolved oxygen criterion and a fecal coliform bacteria criterion. Currently, the State of Florida is pursuing the development of numeric nutrient water quality criteria for all surface waters.

The state waters surrounding the Florida Keys have been designated as Outstanding Florida Waters (State of Florida Rule 62-302.700). By regulation, it is the policy of the Florida Department of Environmental Protection to afford the highest protection to Outstanding Florida Waters and to limit their degradation.[6] This designation of waters surrounding the Keys has resulted in the elimination of all direct surface water discharges of pollutants.

Eutrophication

Eutrophication has been defined as an increase in the rate of the supply of organic matter to an ecosystem. Eutrophication often progresses through a sequence of stages:

1. Enhanced primary production;
2. Changes in plant species composition;
3. Dense blooms of phytoplankton;
4. Death of cells causing the bloom;
5. Anoxic (no oxygen) conditions as organisms die;
6. Adverse effects on fish and invertebrates; and
7. Changes in the benthic community.[7]

Nutrients affect water quality

Too many nutrients

Nutrients, such as nitrogen and phosphorus, are essential for all living matter. Growth of plants is generally limited by the lack of one or more nutrients, and new plant growth depends on recycling of nutrients or receiving new nutrients from external sources. If new nutrients get into surface waters, they become available for use by the marine ecosystem. Small additions may cause inconsequential changes, but if continued or increased, they become pollutants as they disrupt the natural nutrient balance and cause unacceptable changes in community structure (e.g., algal blooms).

Generally, it is the total amount of nutrients entering a waterbody, not necessarily the absolute concentration, that can overload the ecosystem and cause changes. When the system can no longer absorb increased amounts of additional nutrients without significantly changing the structure and function of the ecosystem, the threshold of nutrient assimilative capacity is reached. The Total Maximum Daily Load for a waterbody is the total pollutant load that can be added and/or discharged to those waters without exceeding the ability of the waterbody to assimilate that load and still be in compliance with water quality standards.

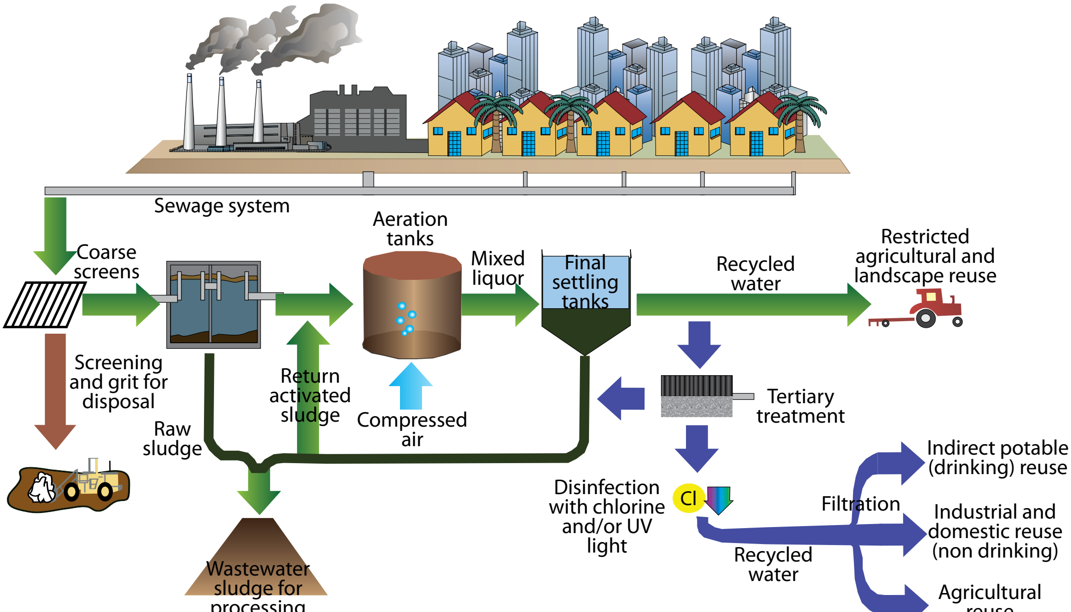
Nutrients may be limiting

Plants stop growing when they do not receive the required nutrients. The nutrient in least supply is called the “limiting nutrient.” Florida Bay exhibits a gradient in limiting nutrients. To the west, phosphorus is plentiful from the waters of the Southwest Florida Shelf, and nitrogen is limiting. To the east, nitrogen is plentiful from water flowing from tidal creeks and through the mangrove fringe, mostly as dissolved organic nitrogen, and phosphorus is bound by the carbonate sediments and is not readily available.

Phytoplankton blooms in Florida Bay historically have developed in the central regions of the Bay when light, nutrients, or dissolved organic matter are not limiting. Diatoms dominate phytoplankton blooms in the western portion of the Bay where relatively high amounts of silicate from freshwater discharges occur. Phytoplankton dominated by diatoms support relatively healthy populations of large fish. Since the early 1990s, phytoplankton blooms in central Florida Bay are dominated by cyanobacteria that support a food chain consisting of smaller species of fish.

During road construction on U.S. Highway 1 entering the Florida Keys (18-Mile Stretch), water held in soils as well as freshwater runoff during Hurricane Rita (2005) resulted in large amounts of phosphorus being delivered to Barnes Sound and Blackwater Sound in the eastern portion of Florida Bay, an area normally limited by phosphorus. The results were a large and persistent phytoplankton bloom and seagrass mortality, probably from shading by dense phytoplankton concentrations.

In 2002, a plankton bloom, called a “blackwater event” because of its color in aerial photographs, formed on the Southwest Florida Shelf. Monitoring and remote sensing data revealed that it occurred as a result of a declining red tide event that moved south along the Southwest Florida Shelf at the same time that a seasonally occurring diatom bloom was triggered in western Florida Bay due to a normal, seasonal discharge from Shark River. This resulted in a large bloom consisting of a mix of toxic dinoflagellates (*Karenia brevis*, the red tide organism) and



Adapted from sewagetreatment.us

A modern central collection and wastewater treatment plant can remove nutrients from wastewater to very low levels (i.e., tertiary treatment) and provide recycled water for agricultural and landscape uses. Many older treatment plants do not provide this level of treatment.

diatoms and lead to the death of sponges and other benthic fauna over a large area.

Water column monitoring has shown that waters immediately adjacent to the Keys have significantly greater amounts of nitrate nitrogen than water farther offshore. There are two potential explanations for this. One is an excess supply of nitrate relative to phosphate. Another is nutrients from land-based sources.

Sources of pollution in south Florida waters

More than half of the coastal waters in the nation are moderately to severely degraded by nutrient pollution.[8] Nutrient pollution by nitrogen and phosphorus is the main cause of many coastal problems, including eutrophication, harmful algal blooms, dead zones, fish kills, some shellfish poisonings, and alteration of benthic community structure.

Nutrients and other pollutants can enter south Florida waters from nearfield and farfield sources. Nearfield sources include disposal of sewage (wastewater) and runoff from land (stormwater). Farfield sources include rainwater, air deposition, ocean upwelling events, and deliveries from remote waterbodies (e.g., Gulf of Mexico). Discharges of pollutants can also be classified as point sources and nonpoint sources. Point sources are discharges that occur out the end of a pipe or other fixed conveyance, such as an ocean outfall from a sewage treatment plant. Nonpoint sources occur as diffuse sources, such as stormwater washed off parking lots, highways, and lawns.[9]

J. Stamates - NOAA

Land-bases sources of pollution may enter coastal waters through navigation inlets, such as the water flowing out of Boynton Inlet on an ebbing tide.

A primary source of pollutants to coastal waters is from sewage. Septic tanks are wastewater systems for individual households (on-site systems) that can only remove a small amount of nutrients, even when properly installed with drainfields that consist of adequate soil to bind nutrients and keep them from entering surface or groundwater. However, septic tanks do not work well in rocky soils (e.g., Florida Keys) or areas with a high groundwater table (e.g., coastal areas), and they are a significant source of nutrient pollution in many locations. Cesspools are unlined holes in the ground into which wastewater is discharged; they are illegal and provide no nutrient removal. Neither septic tanks nor cesspools remove bacteria or viruses from their effluent.

Sewage treatment plants can be classified as package plants and regional plants. All sewage treatment plants are required to provide basic disinfection of their effluent before discharge. Historically, package plants provided treatment of sewage for facilities such as motels, condominiums, and restaurants throughout south Florida. In general, most package plants and small municipal plants settle and remove solids from wastewater but do not provide significant removal of dissolved nutrients from their effluent (i.e., secondary treatment). Advanced Wastewater Treatment plants do remove particulate and dissolved nutrients to very low levels (i.e., tertiary treatment). Some large municipal treatment plants in south Florida provide Advanced Wastewater Treatment.

Wastewater from septic tank systems and cesspools is disposed into the groundwater. Proximity of septic tanks and cesspools near open waters results in rapid movement of wastewater into surface waters, such as residential canals or other nearshore waters. Disposal from sewage treatment plants is permitted by the State of Florida and can be discharged directly into surface waters (open water

W. L. Kruczynski - EPA

Marathon Marina, Florida Keys, is a member of the Florida Clean Marina Program and provides pump-out services at each slip and for transient vessels. The Florida Clean Marina Program brings awareness to marine facilities and boaters regarding environmentally friendly practices intended to protect and preserve natural environment of Florida. Marinas, boat yards, and marine retailers qualify for the Clean Marina Program by demonstrating a commitment to implementing and maintaining best management practices.

discharge) or into shallow or deep injection wells.

Several large municipal treatment plants in southeast Florida have permitted open water discharges into the Atlantic Ocean and collectively have been discharging an average of about 1.4 billion liters (360 million gallons) per day of treated wastewater for decades. The outfall pipes discharge from 1.6 – 4.8 kilometers (1 – 3 miles) offshore within the zone of coral growth and the flow direction of the discharges is to the north, except when short-lived counter currents develop off the Florida Current. The ocean outfall at Delray Beach was eliminated in 2009; however, ocean outfalls remain at Miami-Dade Central, Miami-Dade North, City of Hollywood, Broward County, and Boca Raton. Significantly, the Governor of Florida signed a bill in 2008 that became the Leah Schad Memorial Ocean Outfall Program (Chapter 2008-323, Laws of Florida) that prohibits construction of new ocean outfalls and sets a timeline for elimination of existing wastewater outfalls by 2025. It also requires that wastewater previously discharged be beneficially reused. Implementation of this law will decrease potential harmful impacts to marine life and benefit onshore freshwater systems. The South Florida Coral Reef Initiative and the Florida Area Coastal Environment Program are monitoring to assess impacts of land-based sources of pollution to coastal waters of southeast Florida.

Injection wells provide a conduit for wastewater to the underlying deep groundwater. The groundwater in the Florida Keys flows toward the Atlantic Ocean. Nutrients in effluent injected into groundwater are diluted approximately one million to one before they reach surface waters.[10]

Disposal of wastewater from live-aboard and transient vessels is a localized problem in marinas or anchorages. Most marine sanitation devices on boats provide low levels of treatment (e.g., basic disinfection) and discharges may contain relatively high concentrations of nutrients as well as bacteria and viruses. Because of public health and eutrophication problems associated with these discharges, all state waters in the Florida Keys were declared a no-discharge zone in 2002, requiring that holding tanks on live-aboard vessels be pumped out and the effluent disposed at authorized facilities. Pumped out wastes are transported to land-based, permitted wastewater treatment facilities

S. Spring - Palm Beach County Reef Rescue

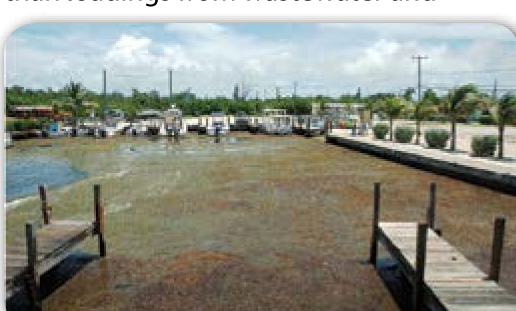
The Delray Beach ocean outfall discharged sewage wastewater into nearshore ocean waters for 45 years before it was retired in 2009.

for treatment and disposal. The National Oceanic and Atmospheric Administration has banned discharge from marine sanitation devices in federal waters of the Florida Keys National Marine Sanctuary.[11]

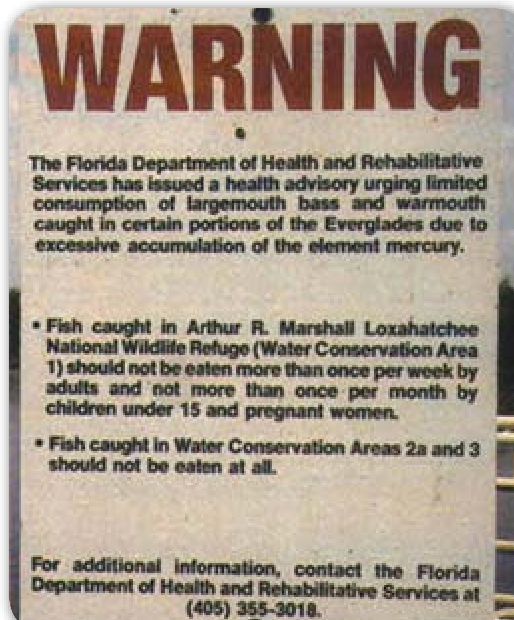
Stormwater is a major source of pollutants to surface waters nationally. Nonpoint source runoff typically contains substances such as pesticides, herbicides, organic debris, silt, nutrients, metals, and oils. The amount of pollutants entering surface waters from stormwater is largely a function of rainfall quantity, imperviousness of the substrate, and land use. In south Florida, the main pollutants include oil, greases, and heavy metals from roads, bridges, parking lots, and other paved areas and fertilizers, pesticides, and herbicides from developed and agricultural areas.

Weed wrack consists primarily of detached blades of seagrasses that are wind driven into floating mats. These mats can become trapped along shorelines and in canal systems and basins along the windward side of coastlines. Decomposition of weed wrack removes oxygen from the water, releases nutrients, and can form toxic hydrogen sulfide gas. Nutrient loading from weed wrack into canals and other nearshore waters has not been quantified.

Waters of south Florida are connected to other geographic areas by ocean currents. Total nutrient loads from farfield sources, such as the Gulf of Mexico and oceanic upwellings, may be greater than loadings from wastewater and stormwater. However, external nutrient inputs are usually more diffuse than land-based, human-induced sources. Currents can also deliver toxic contaminants, including pesticides, heavy metals, and oil from remote locations. There are few data documenting that threat, but vigilance and cooperation within the region are required to identify and minimize sources.


W.L. Kruczynski - EPA

Seagrass shed some of their leaves annually. Floating leaves (weed wrack) can accumulate in boat basins, residential canals, and along shorelines and are a source of organic loading to nearshore waters.



Florida Department of Health

Florida Department of Health issues warnings to limit the consumption of fish from areas contaminated with mercury.

Mercury is a toxic contaminant that is globally dispersed. Atmospheric deposition is the main source of mercury to marine waters in south Florida. Solid waste incinerators and coal-fired power plants are the main sources. Mercury is biomagnified through food webs and 12 states, including Florida, have statewide advisories for mercury contamination of fish in their coastal waters.[12]

Other heavy metals have not been a concern in south Florida waters. Pesticides, including chemicals used in mosquito control, are known to be toxic to aquatic organisms. However, there is little information on the amount and effects of residual pesticides that reach marine waters.

Water pollution problems and solutions for south Florida

There are three main problems with wastewater pollution of surface waters: fecal contamination (e.g., health risk); nutrient enrichment and organic loading (e.g., eutrophication, low dissolved oxygen); and presence of pharmaceuticals and personal care products, including endocrine disruptors. Presence of total fecal coliform bacteria above the State of Florida standard (200 colonies per 100 milliliters [3.4 fluid ounces] of water, monthly average; sample maximum 800 colonies/100 ml) is indicative of contamination by untreated or inadequately treated sewage and is a public health concern.[13] However, the fecal coliform standard was developed for freshwater, and its use for marine waters is less than ideal. Several states have adopted an *Enterococcus* bacteria standard that may be a better indicator of fecal contamination in marine waters.[14] Recent results suggest that replacement of a total coliform standard with an enterococci standard would be more protective of public health.[15] Normally, when fecal coliform bacteria are present in marine waters, it is an indicator of very recent fecal contamination. Low concentrations of fecal coliform bacteria should not necessarily be equated to low abundance of bacterial or viral pathogens.


M. White - FKNMS

Tropical marine coral communities have evolved and thrive in clear waters with relatively low concentrations of nutrients.

Fecal bacteria are found in residential canals and marinas. Because animals (e.g., dogs, raccoons, birds) have coliform bacteria in their feces, analyses of chemical "fingerprints" of the bacteria are required to determine their sources. Because most viruses are species specific, use of human intestinal viruses is a more reliable indicator of human fecal contamination. Eighteen of 19 nearshore and canal locations sampled in the Keys and groundwater samples at the bank reef off Key Largo were found to contain human pathogenic viruses.[16]

Based on evidence that poor water quality in the nearshore waters of the Florida Keys is related to poor wastewater management, the Florida Legislature passed 99-395 Laws of Florida, requiring that all sewage facilities in Monroe County, including septic tanks and cesspools, upgrade and comply with promulgated treatment and disposal standards by July 1, 2010. The treatment and disposal standards conform to readily available, cost effective technologies that are used elsewhere in Florida, including Tampa Bay and the Indian River Lagoon. Although progress is being made, many municipal facilities in Monroe County remain incomplete, and the deadline has been extended until 2015.[17]

Tropical marine coral, hardbottom, and seagrass communities have evolved and thrive in relatively low nutrient (i.e., oligotrophic) conditions. Integral species in these communities efficiently absorb low concentrations of nutrients and outcompete other less adapted species. It has been argued that nutrient overenrichment is a major cause of the worldwide coral reef decline because of observations that degraded coral reefs exhibit a shift from high coral cover with low algal cover to low coral cover with high algal cover. But are the algae causing the coral decline? The extent to which nutrients are related to coral decline is the subject of much debate. Overenrichment can be the cause of localized reef degradation. Other factors such as decreased abundance of grazing fish and sea urchins and temperature stress (e.g., bleaching) may create more open substrate for algal colonization. Sedimentation can weaken corals and prevent recruitment. Coral diseases can affect corals weakened by bleaching or other stresses. Impacts that lead to coral death as well as those that reduce herbivory leave substrate open to colonization by algae and/or make effects of low level enrichment more severe.[18] Because the uptake of nutrients in an oligotrophic system is rapid and turnover of nutrients is very efficient, nutrient concentrations in the water over reefs receiving enrichment can be quite low and may not be detectable using traditional water quality analyses.

C. Kelble - NOAA

Researchers sampling water quality in Florida Bay.

Several different scientific studies have been performed in the Florida Keys to determine whether nutrient enrichment from land-based sources is impacting the bank reef. Water quality monitoring has provided ample evidence demonstrating that canals and other nearshore waters have high nutrient, chlorophyll, and bacteria concentrations that are the result of poor wastewater and stormwater treatment practices on land. Evidence is mounting that seagrasses at some nearshore locations in the Keys are experiencing nutrient enrichment, and as a result, benthic macroalgae are increasing in some locations. Analysis of surface water quality data in the Florida Keys demonstrates that inorganic nitrogen is greatest nearshore and decreases toward the outer reef tract, suggesting a land-based source.

However, results of other methods suggest that sewage from the Keys is reaching offshore reefs. Studies investigating the distribution of human pathogenic viruses have demonstrated that groundwater at the bank reef off Key Largo contains human viruses.[19] It is believed that the viruses found can come only from human sewage through the groundwater. Thus, groundwater containing diluted nutrients may reach the bank reef. This observation is supported by finding human viruses in the mucus of corals growing on the bank reef.[20] Coral mucus acts as a culture medium for bacteria and viruses. Thus, it appears that there may be conduits of rapid transport of groundwater from shore to the Florida Keys Reef Tract, but nutrients from wastewater are very diluted and may be rapidly taken up when they reach surface waters.

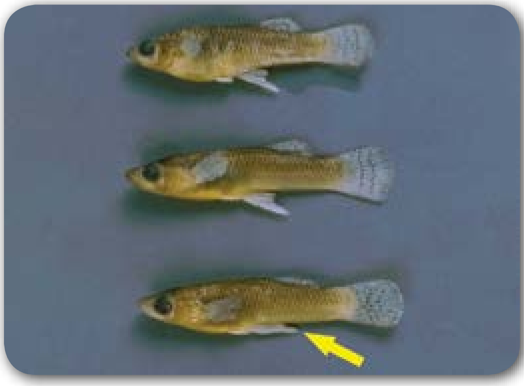
Recognizing the importance of reefs in southeast Florida, the South Florida Coral Reef Initiative formed a Land-Based Sources of Pollution Focus Team to addresses impacts to corals resulting from both point and nonpoint land-based pollution sources, and a Local Action Strategy was developed.[21] Projects in the Local Action Strategy focus on characterizing the extent and condition of the coral reef community, and quantifying, characterizing, and prioritizing the land-based pollution sources. Results will lead to the development of strategies that will reduce the impacts of land-based sources of pollution. Increased public awareness and understanding of the effects of these sources of pollution on water quality and coral reefs are essential to successful implementation of the strategies.

There is a widespread occurrence of low concentrations of pharmaceuticals, hormones and their metabolites, and other chemicals in the aquatic environment. Their source is from human usage, discharges, and excretions. Over-the-counter and prescription medications are present in human sewage and can contaminate receiving waters. Fungicides, disinfectants, and veterinary products are also common.[22]

Pharmaceuticals, steroids, and personal care products were found to be common in the Miami River and a canal system in the Florida Keys. Caffeine and cholesterol were particularly ubiquitous, and higher concentrations of caffeine were linked to locations with documented water quality problems. Thus, caffeine may be a particularly good indicator of sewage contamination.[23]

Some compounds found in water are known or suspected endocrine-disrupting chemicals. Endocrine disruptors are chemicals that may interfere with the endocrine (i.e., hormonal) system and produce adverse developmental, reproductive, neurological, and immune effects in both humans and wildlife. A wide range of substances, both natural and humanmade, can cause endocrine disruption. Endocrine disruptors may be found in many everyday products, including plastic bottles, metal food cans, detergents, flame retardants, food, toys, cosmetics, and pesticides. Endocrine disruptors may result in human health effects, including lowered fertility. Their effects on aquatic organisms include disruption of breeding cycles and changes in sex.[24, 25,26]

Other changes in water quality can result in dramatic changes to an ecosystem, such as changes in temperature, salinity, and turbidity. Turbidity decreases with distance from shore. Channels and passes throughout the Florida Keys had higher nutrient concentrations, phytoplankton, and turbidity than areas located off land.



S. A. Bortone - GCMFC

A dramatic effect of endocrine disruptors that occur in water is their ability to disrupt endocrine-mediated processes, such as reproduction, including sex determination and development of sexual characteristics. The three female mosquito fish (*Gambusia affinis*) have been "masculinized" and have developed an elongated anal fin (i.e., gonopodium) (yellow arrow) that is an organ normally used by male fish for sperm transfer. Masculinized female mosquito fish were first observed in a coastal stream receiving paper mill effluent. The effluent contained steroid analogs and precursors that adversely affected hormonal pathways.

Florida Bay has been a source of nutrient-rich and turbid waters to the Florida Keys for the last few thousand years.

Prior to the construction of the extensive drainage canal network in south Florida, offshore springs discharged large quantities of fresh groundwater into Biscayne Bay as either spring flow or the continuous seepage of fresh groundwater along the coast. When drainage canals were constructed to reduce flooding in the area, the mechanism for transporting water to the Bay was significantly altered, and rather than receiving a continuous supply of fresh groundwater, Biscayne Bay now receives wet season pulses of canal discharge. The change in timing and location of freshwater flow to the Bay has harmed the Biscayne Bay ecosystem. Organisms that live there have either adapted to wide fluctuations in salinity, flee when conditions become unfavorable, or die.[27] It is hoped that completion of the Comprehensive Everglades Restoration Plan will restore the quantity, quality, timing, and distribution of freshwater flows to downstream sources, including Florida Bay and Biscayne Bay.

Water quality is monitored to assess environmental conditions

Christopher Kelble, Cynthia Heil, and Patricia M. Glibert

All living things on Earth need water to survive. Our bodies are made up of more than 60% water, and we need clean water to drink, grow crops, swim, surf, fish, and sail. Water quality measurements provide an indicator of the nature and health of an ecosystem. Monitoring water quality characteristics allow scientists and managers to keep their "finger on the pulse" of the ecosystem and are determined by measuring a variety of water quality parameters. Measurements allow ecosystem managers to take action prior to ecosystem collapse.

Why we measure water quality

- Establish baseline conditions;
- Detect long-term trends;
- Determine suitability for uses;
- Check compliance with standards; and
- Ensure public health safety.

Most people recognize degraded water quality by characteristics such as discolored water, algal scums, and odors. But degraded water quality may not be easily recognized. For example, contamination by pathogenic bacteria and viruses may make water dangerous for swimming, but the risk is not recognizable without laboratory testing.

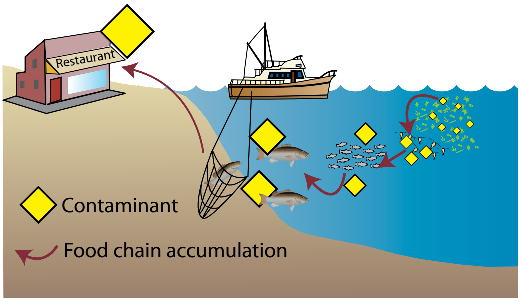
Water quality is also a measurement of the ability of the aquatic system to support beneficial uses. Because many systems differ greatly in their use, what constitutes good water quality is site specific, and water quality is judged by the particular purpose for which the system is being used. In fact, the United States Environmental Protection Agency identifies designated uses (e.g., fishable, drinkable, swimmable) when setting targeted levels for individual water quality parameters. If the water is to be used for drinking, a specific set of chemical parameters are well defined. Waters used by fishing or shellfishing industries are characterized by parameters required to maintain healthy fisheries. For recreational purposes, such as boating, good water quality enhances the aesthetic experience.

Commonly measured water quality parameters

- Temperature
- Salinity
- pH
- Turbidity
- Light attenuation
- Dissolved oxygen
- Chlorophyll *a*
- Total organic carbon
- Total organic nitrogen
- Total nitrogen
- Total phosphorus
- Nitrate
- Nitrite
- Ammonium
- Silicate
- Fecal coliform bacteria

Factors that contribute to degraded water quality can be related to both natural processes and influences of human activities. Many lakes naturally go through a life cycle in which the lakes slowly fill in over geological time. However, that process may be accelerated by human activities, such as those that result in the delivery of increased nutrients to the lake.

In coastal marine systems, human activities, such as population growth and development, often have a detrimental impact on coastal water quality. Increased or changing nutrient delivery can result in algal blooms that discolor the water and decrease light penetration, in turn affecting benthic communities, including seagrasses.



Water quality monitoring can detect contaminants, such as mercury, that can become biomagnified through food webs and is toxic to consumers.

Poor water quality conditions can affect humans in many ways. For example, bathing in waters containing harmful bacteria or consumption of seafood from areas with poor water quality can cause sickness and disease. Contaminants such as heavy metals can be concentrated in seafood through a process called biomagnification.

Different ecosystems have different characteristic water quality regimes. In south Florida, the coastal marine ecosystem is primarily oligotrophic, with low nutrient and chlorophyll concentrations. As such, this ecosystem responds rapidly and significantly to nutrient loads that would be considered small in many other regions. Water quality in the south Florida marine ecosystem is directly influenced by runoff from natural areas, such as creeks and streams, the nearby Everglades ecosystem, and from surrounding urban areas (land-based sources). A comprehensive water quality monitoring program is required to identify and track, and ultimately control, sources of nutrients and other contaminants that enter these waters.

Water quality in south Florida is generally good compared with other areas of the Atlantic coast, even with the major landscape changes that have occurred in south Florida. Recently, seagrass die-off and algal blooms have resulted in degraded water quality in Florida Bay. Given the landscape changes to the watershed, returning Florida Bay to nondegraded conditions is a major challenge of the Comprehensive Everglades Restoration Plan. Completion of the plan is likely to alter the south Florida marine ecosystem. The United States Commission on Ocean Policy concluded that long-term water quality monitoring is the best measure to provide accountability for management actions. Water quality monitoring in the south Florida marine ecosystem must be used to adaptively manage the restoration process to ensure that the most beneficial outcomes are achieved.

R. Butler

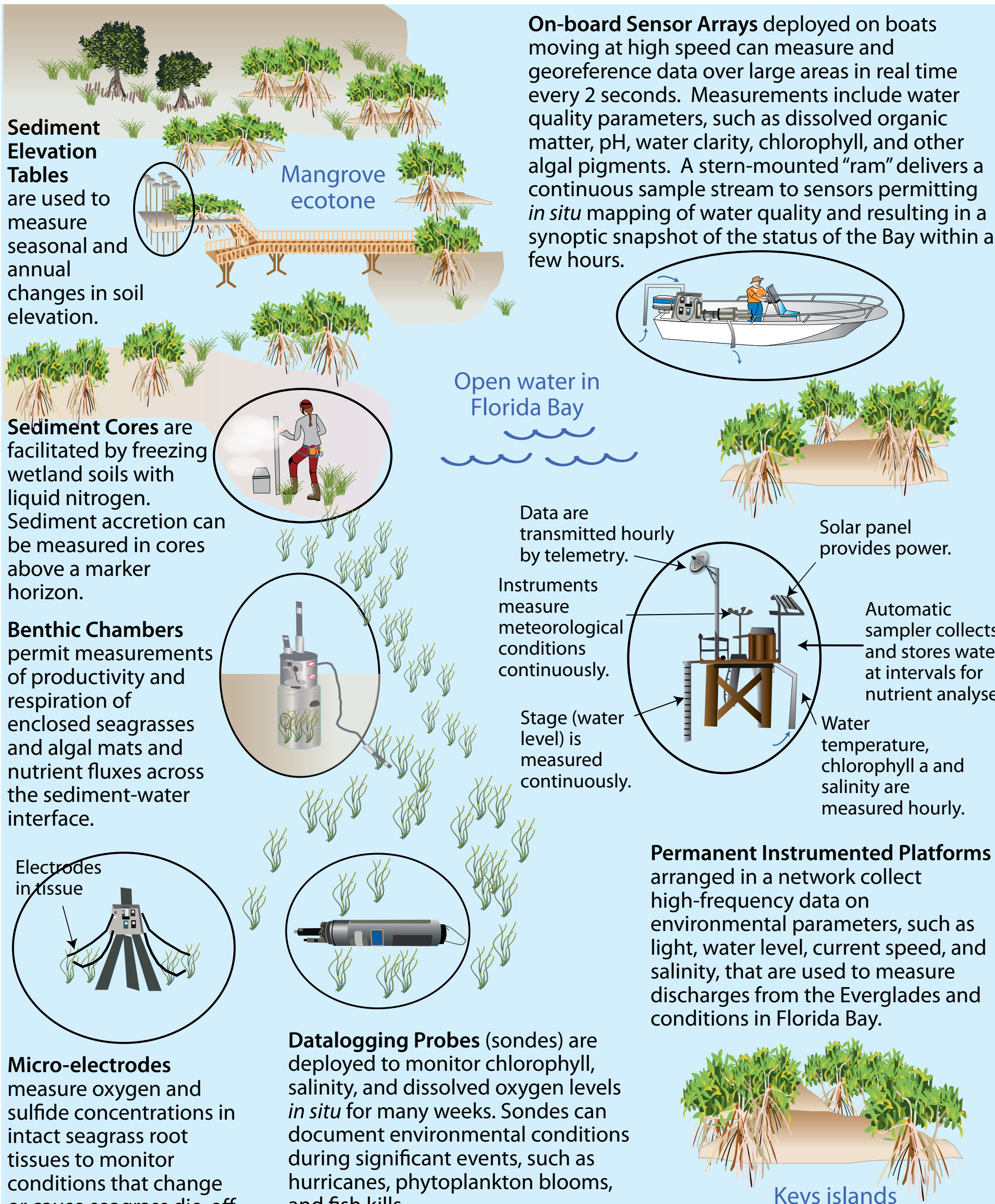
Poor water quality conditions can result in fish kills.

J. Teague - Finatic Charters

Good water quality is required to meet the standards of fishable, drinkable, and swimmable waters.

Field measurements are collected to assess water quality and environmental conditions

Christopher J. Madden and Kevin M. Cunniff



A number of technology tools are used to collect data on various aspects of Florida Bay, including real-time mapping, short-term measurement of ecological processes, and mid- and long-term instrument deployments to capture ecosystem metabolism, rate processes, and episodic events. A network of instrumented platforms monitors long-term water quality, environmental conditions, and system status.

Nutrients are important water quality parameters

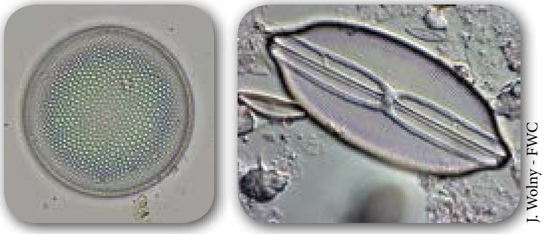
Patricia M. Glibert and Cynthia Heil

Nutrients are essential elements for life. Both plants and animals require a variety of chemical elements and vitamins to grow, maintain their metabolism, and reproduce. Animals ingest their required nutrients; plants absorb them through their cell walls, roots, and leaves. The major nutrients are nitrogen, phosphorus, and carbon as well as sulfur, silicon (for some plants), calcium, magnesium, iron, and potassium, among others. When these nutrients are not sufficiently available to meet the needs of plants or animals, they are considered to be limiting for growth or production of new biomass. The nutrients of major concern for water quality are nitrogen and phosphorus.

Liebig's Law of the Minimum (1840)

This law states that the nutrient available in the least quantity relative to the needs of the organism is the growth-limiting nutrient.

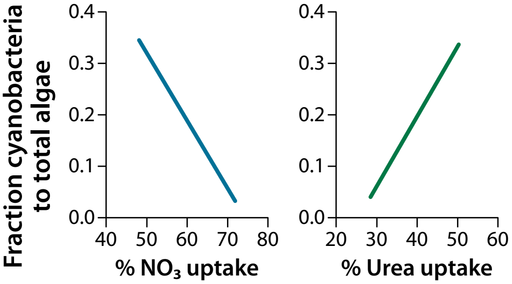
Nitrogen and phosphorus are nutrients that are present in the environment in a variety of forms. The atmosphere is comprised of about 78% nitrogen in the form of nitrogen gas (N_2), but this form is only available to organisms that have the unique capability to "fix" this gas (e.g., legumes, some bacteria) into more chemically active forms. The most common available form of nitrogen is nitrate (NO_3^-), but nitrite (NO_2^-) or ammonium (NH_4^+) are also common biologically available forms. Nitrogen can be found complexed to other elements, forming large molecules that may or may not be biologically available. Such complex molecules include urea, amino acids, proteins, pigments, and humic acids. Unlike nitrogen, phosphorus is not available as a gas. Phosphate (PO_4^{3-}) is the most common biologically and chemically



Diatoms are common unicellular planktonic plants in south Florida waters. The cells are encased with unique cell walls (frustules) made of silicate (silicic acid).

available form, and phosphate can be complexed by other molecules.

Different plants and animals have different requirements for nutrients as well as different nutrient preferences. Furthermore, the proportion in which they are available is important to their growth. By way of analogy, when fertilizers (i.e., nutrients) are applied in gardens, it is common to use different formulations, depending on whether one is growing grass, tomatoes, or roses. Preferences also exist even within the microbial plants. Some, such as diatoms, have an absolute requirement for silicon, whereas other microscopic plants, such as dinoflagellates, do not. Some diatoms also tend to prefer nitrogen in the form of NO_3^- whereas dinoflagellates typically prefer nitrogen as NH_4^+ or urea.



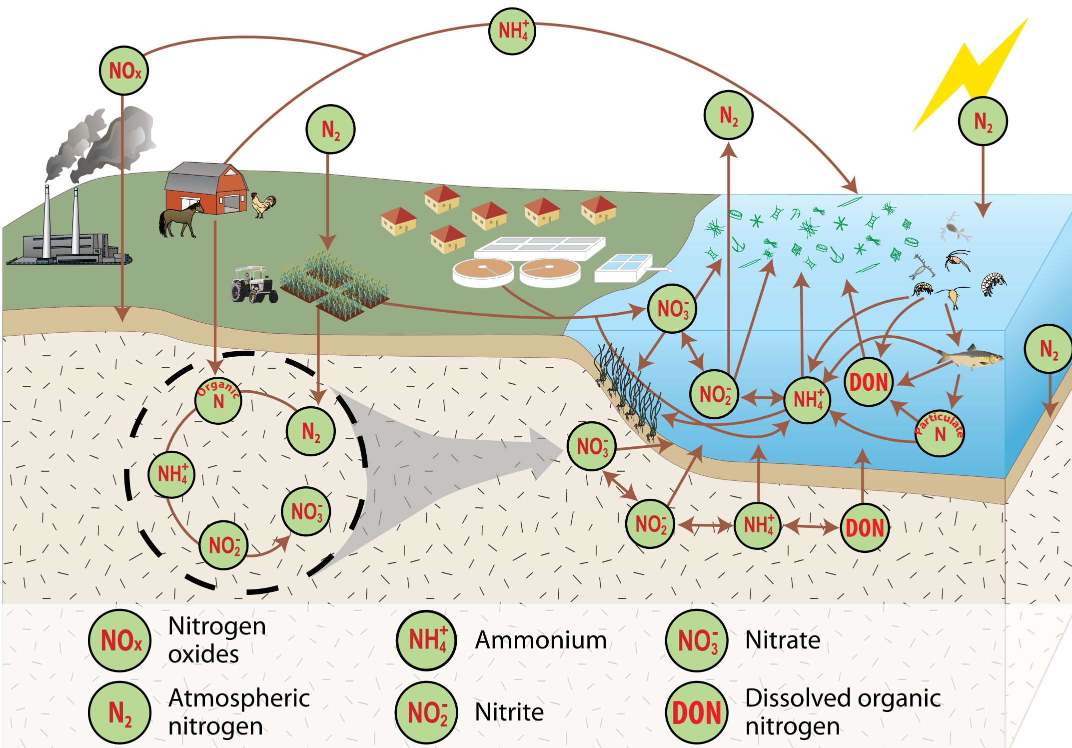
Cyanobacteria, such as *Synechococcus*, have a preference for urea over nitrate (NO_3^-). These data from eastern Florida Bay show that NO_3^- uptake is high when the fraction of cyanobacteria is low, but that urea uptake is proportionately high when cyanobacteria make up a higher proportion of the total algal community.

Nutrients cycle through the environment

Patricia M. Glibert and Cynthia Heil

Nutrients cycle through the air, land, and water in various forms. Most transformations are mediated by biological activity, particularly by microbes. Nitrogen and phosphorus are two nutrients that are important in biological processes and ecosystem structure and function.

Nitrogen gas (N_2) makes up approximately 78% of the atmosphere on Earth. It is converted by some plants (e.g., legumes) and nitrogen-fixing bacteria into ammonium (NH_4^+). Ammonium may be taken up directly by plants, including phytoplankton, but a large fraction is nitrified by bacteria to nitrite (NO_2^-) and eventually nitrate (NO_3^-). Both forms of nitrogen also may be used directly by plants. Once in plants, nitrogen is used to manufacture proteins, DNA, and other molecules needed to sustain life. Plant nitrogen is consumed by animals, and eventually excreted or released as organisms die and decay. Some of the released nitrogen may be in the form of fairly complex molecules; some molecules can be broken down and taken up directly by plants, and some cannot. Some of NO_3^- also may be denitrified by microbial activity and released to the atmosphere as N_2. The process of denitrification, however, yields many intermediate nitrogen



Nitrogen cycle: Nitrogen gas in the atmosphere is fixed by some plants and nitrogen-fixing bacteria into ammonium. Ammonium can be taken up by some plants or converted to nitrate and taken up. Some nitrate is denitrified and released back to the atmosphere as nitrogen gas. Animals excrete nitrogen in waste products and as plants and animals die and decompose, ammonium and other nitrogen compounds can enter the cycle. Too much nitrogen can cause eutrophication of waters.

compounds during the conversion from NO_3^- to N_2. Nitrous oxide (N_2O) is one such compound and is a greenhouse gas.

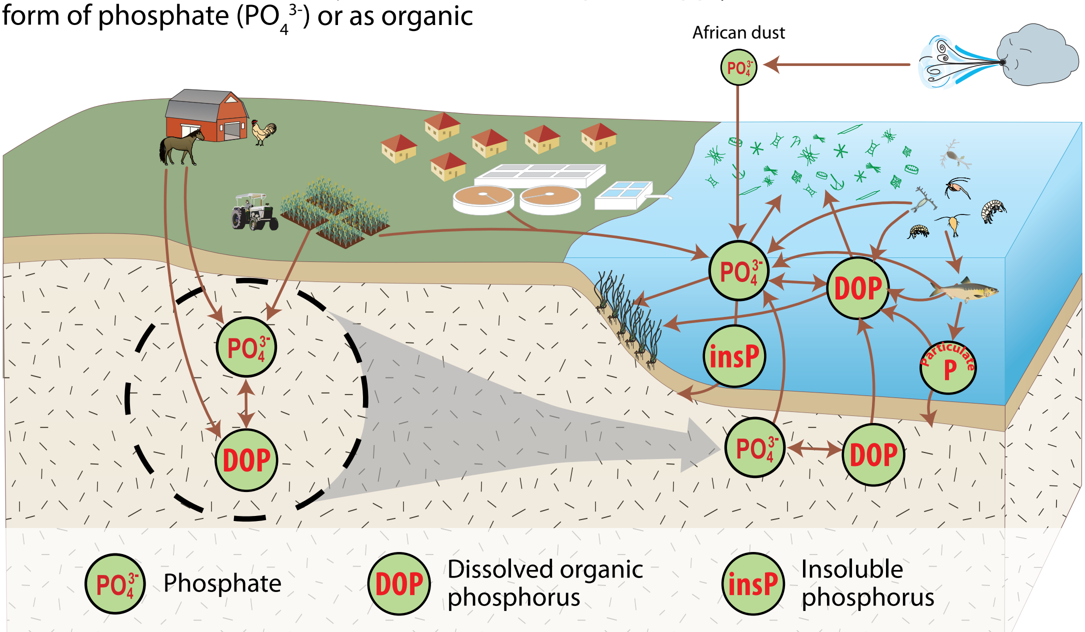
Nitrate accumulates in deep ocean waters over long periods of time. When that water reaches the surface through upwelling, it is taken up by algae and other plants and represents a new form of nitrogen to the surface waters. In contrast, ammonium generally is considered to be a regenerated form of nitrogen because it is continually recycled in water by microbial grazing and release of nitrogen by consumers.

Unlike nitrogen, there is no gaseous form of phosphorus. The major phosphorus reservoirs are in guano deposits (i.e., bird droppings) and in rocks. Phosphorus can be released from rocks through weathering and leaching and may be carried by runoff to waters. Mining of phosphorus for fertilizer has increased its availability in the environment. Phosphate like nitrate also accumulates in the deep ocean over time.

Phosphorus is taken up by plants in the form of phosphate (PO_4^{3-}) or as organic phosphorus, passed through the food chain, and released by excretion and decomposition. When plants and animals die, bacteria decompose their bodies, releasing some of the phosphorus back into the soil or water.

Human activities are causing changes to the nitrogen and phosphorus cycles and the amount of nutrients that are stored in different reservoirs. The industrial manufacture of fertilizer converts N_2 to ammonia (NH_3). The rate of industrial production of fertilizers has escalated in recent decades, and this pathway now exceeds natural fixation as the major path by which N_2 is removed from the atmosphere. Additionally, humans are altering the nitrogen cycle by burning fossil fuels and forests, which releases N_2O and other forms of nitrogen to the atmosphere.

The use of fertilizers can cause nutrient loading as they wash into nearby waterbodies. The increased nutrient levels cause plants to grow rapidly until they use up the supply of nutrients.



Phosphorus cycle: Main reservoirs are rocks and bird guano deposits. Phosphate can be dissolved by water and be available for uptake by terrestrial or aquatic plants. Plants are eaten by animals and release particulate organic phosphorus that can be recycled or deposited in sediments and become incorporated into sedimentary rock.

Too many nutrients result in eutrophication

Patricia M. Glibert and Cynthia Heil

Eutrophication means an increase in the rate of supply of organic matter to an ecosystem. The term is used in ecology to describe the natural aging of ecosystems, such as lakes. The natural fate of a deep, nutrient-poor (i.e., oligotrophic) lake is to accumulate organic matter and become nutrient-rich (i.e., eutrophic), which over geological time scales leads to the development of a pond and eventually a marsh ecosystem. The term eutrophication is also used to describe the process of nutrient pollution by humankind (i.e., when excess nutrients are added to an ecosystem, resulting in an increase in primary productivity or algal biomass). An overgrowth of plant material, including phytoplankton, can detrimentally alter an ecosystem in multiple ways. Excess phytoplankton (i.e., blooms) may die and decompose, leading to the loss of oxygen in the water (i.e., hypoxia), and smother and kill corals, sponges, and other organisms, resulting in an alteration of the entire structure and function of the ecosystem. Eutrophication is a process, not an endpoint.

Eutrophication

"The numbers and kinds of plants in the Bay are controlled, principally, by the abundance of the several kinds of nutrients and, to a lesser extent, by the forms in which they are present. Fertilizer is good, more fertilizer is better, but only up to a point. Once the 'broth' becomes too rich, the composition of species alters. The balance is delicate, and changes can be rapid…More is no longer better. Enrichment has become eutrophication." (J.R. Schubel, 1981)

Human activities can accelerate the rate at which nutrients enter ecosystems, and there are many sources of nutrients that can lead to eutrophication. Runoff from

W. L. Kruczynski - EPA

Excessive fertilization can disrupt the structure and function of aquatic ecosystems by causing excess primary productivity as evidenced by this eutrophic pond.

agriculture and development, pollution from septic systems and sewers, and other human-related activities increase the inputs of both inorganic nutrients and organic substances into terrestrial and aquatic ecosystems.

Eutrophication of waterbodies can be caused by both nonpoint (e.g., land runoff) and point sources of pollution containing phosphorus and nitrogen. Humankind has increased the rate of phosphorus loading to coastal waters by 4 times, and that of nitrogen by about 20 times, mainly due to agricultural fertilizer production and application. From 1950 – 1995, 544 million metric tons (600 million tons) of phosphorus were applied to the Earth surface, primarily on croplands. Nearly half of the nitrogen fertilizer in the world has been produced since 1985. Much of the excess fertilizer finds its way into groundwater and surface waters and causes eutrophication of receiving waters. Elevated atmospheric compounds of nitrogen from burning fossil fuels can increase nitrogen availability.

Stringent regulatory controls of point and nonpoint sources are required to minimize excess nutrient pollutants from entering waters. The goal of these regulations is to improve the water quality so that the waters remain or become fishable, swimmable, and drinkable resources for future generations.

Florida Bay receives nutrients from many sources

David T. Rudnick, Stephen P. Kelly, and Robin Bennett

Nutrient availability for primary producers and nutrient dynamics in Florida Bay are driven by the exchange of nutrients with adjacent regions and internal nutrient cycling. Nutrients enter the Bay from the south Florida peninsula via freshwater flow through the Everglades and adjacent canals, the Gulf of Mexico, the Atlantic Ocean, the Florida Keys, groundwater, and the atmosphere (via rainfall). Nitrogen and phosphorus are key nutrients that typically limit estuarine productivity and can determine the ecological condition (i.e., health) of the Bay. Excess phosphorus and/or nitrogen can fuel phytoplankton (i.e., microalgae) blooms and can cause the Bay to shift from a seagrass-dominated system to a system where algae in the shallow water column dominates visually and ecologically. In much of Florida Bay, productivity is limited by phosphorus availability, but nitrogen also can be an important determinant of Bay condition.

Very little phosphorus enters Florida Bay from the Everglades; the overwhelming source of phosphorus is derived from the inflow of Gulf of Mexico waters. The amount of phosphorus from the Gulf has been estimated using computer models of water exchange, and concentrations decrease in Florida Bay from west to east, consistent with the estimated importance of the Gulf source.

Nitrogen inputs can be from many sources. Nitrogen inputs from the Everglades can be significant, with estimated values roughly similar to those from the atmosphere and Gulf of Mexico. However, most nitrogen from the Everglades is in a dissolved organic form and not readily available for uptake by algae or seagrass. Within the Bay, dissolved organic nitrogen can be transformed by biotic and abiotic processes, making it available for uptake.

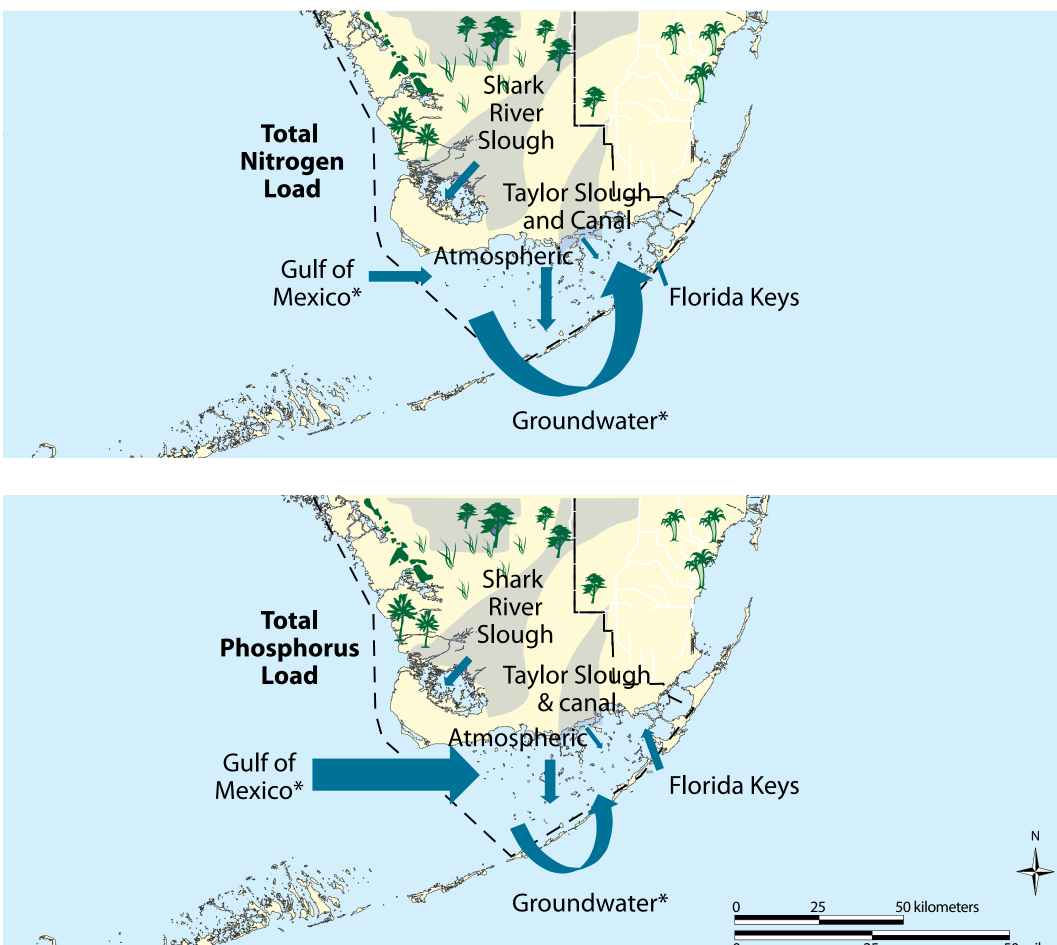
NASA

Florida Bay can be divided into zones based on similar water quality characteristics.

Water Quality

In contrast, nitrogen inputs from the atmosphere are mostly in the form of dissolved inorganic nitrogen and are readily available for uptake. The input of saline groundwater from beneath the Bay also may be an important nutrient source (especially for nitrogen), but the amount of this input is very difficult to measure, and the estimates are highly uncertain.

Nutrient inputs to the Bay are affected by both natural and anthropogenic events, including water management activities. Periods of drought decrease the amount of freshwater inputs from the Everglades and the atmosphere. Drought can result in high salinity stress and drying of wetlands that inhibit plant productivity and increase the decomposition of organic matter. With the first substantial rainfall events after a drought, nutrient inputs from the freshwater and saline coastal wetlands can be elevated. Tropical storm or hurricane events can be particularly important drivers of nutrient inputs to Florida Bay. Heavy rainfall associated with these storms increases runoff from the Everglades and stormwater releases from canals. Large amounts of leaf litter from wetland and estuarine plants and nutrients from sediments and groundwater are also mobilized during storms.



Estimates of the annual exchange of and total nitrogen (top) and total phosphorus (bottom) at the boundaries of Florida Bay. The width of the arrow indicates the relative contribution of each input. Estimates for groundwater and the Gulf of Mexico inflows (*) are more uncertain than other estimates. Groundwater inputs may include recycled Bay nutrients.

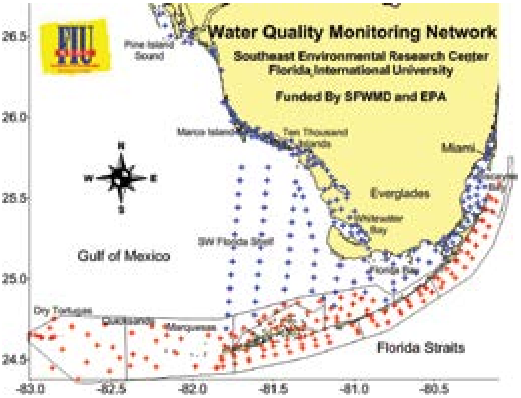
Spatial patterns of water quality in the Florida Keys National Marine Sanctuary

Joseph N. Boyer and Henry O. Briceño

Water quality has been measured at 155 fixed stations in the Florida Keys National Marine Sanctuary since 1995. Stations in the Sanctuary are part of a network of other fixed sampling sites (175 additional stations) distributed throughout the estuarine and coastal ecosystem of south Florida. The purpose of the sampling program is to address concerns in regional water quality that cross and overlap political boundaries. Biscayne Bay, Florida Bay, Whitewater Bay, and Ten Thousand Islands are sampled monthly, whereas the Sanctuary and the Southwest Florida Shelf are sampled quarterly. One of the products of this combined effort is a comprehensive evaluation of nutrient and phytoplankton biomass distributions throughout south Florida coastal waters.

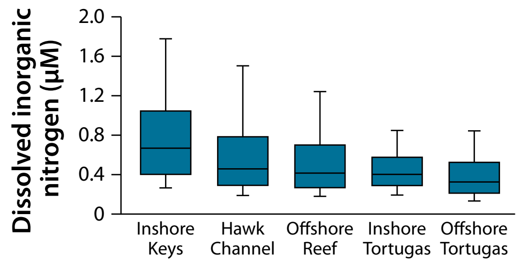
Variables currently being measured include temperature, salinity, dissolved oxygen, dissolved inorganic nitrogen (including ammonium, nitrate, nitrite), total organic nitrogen, soluble reactive phosphorus, total phosphorus, total organic carbon, chlorophyll *a*, turbidity, and light extinction.

One important finding from this monitoring project is documentation of elevated nitrate in the inshore waters of the Keys. This result was evident from



FIU

Locations of fixed water quality monitoring stations in south Florida. Stations in the Sanctuary (red) have been sampled quarterly since 1995.



FIU

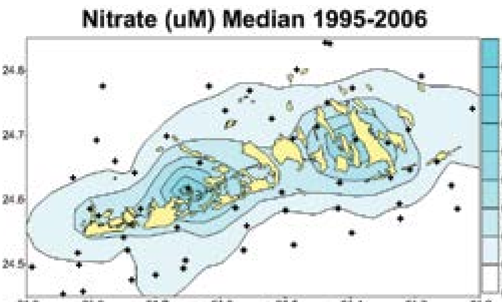
Dissolved inorganic nitrogen is highest in waters near the Keys, which is consistent with a nearshore or land-based source.

the first sampling event in 1995 and continues to be a characteristic of the ecosystem. Interestingly, this gradient was not observed in a comparison transect in the Tortugas (i.e., no human impact). This type of distribution implies an inshore source of nitrate that is diluted by low nutrient Atlantic Ocean waters. There were no trends in chlorophyll *a* in relation to distance from land.

Declining nearshore-to-offshore trends were observed for dissolved inorganic nitrogen, total organic carbon, total organic nitrogen, and turbidity at all oceanside transects. Total phosphorus concentrations in the Lower Keys transects decreased with distance offshore but increased along transects in the Upper Keys.

Another observation is that elevated nitrate is a regular feature of waters on the Gulf side of the Florida Keys (Backcountry). Some of the highest concentrations are observed in this sparsely populated area. These levels are most probably indicative of waters from the Southwest Florida Shelf moving through this area and because of inputs of nutrients from sediments in this very shallow water column. The fact that phosphorus is limiting to heavy seagrass growth in that area may also result in a buildup of nitrogen in the water column.

Water quality monitoring stations can be grouped as occurring off island landmasses or opposite channels



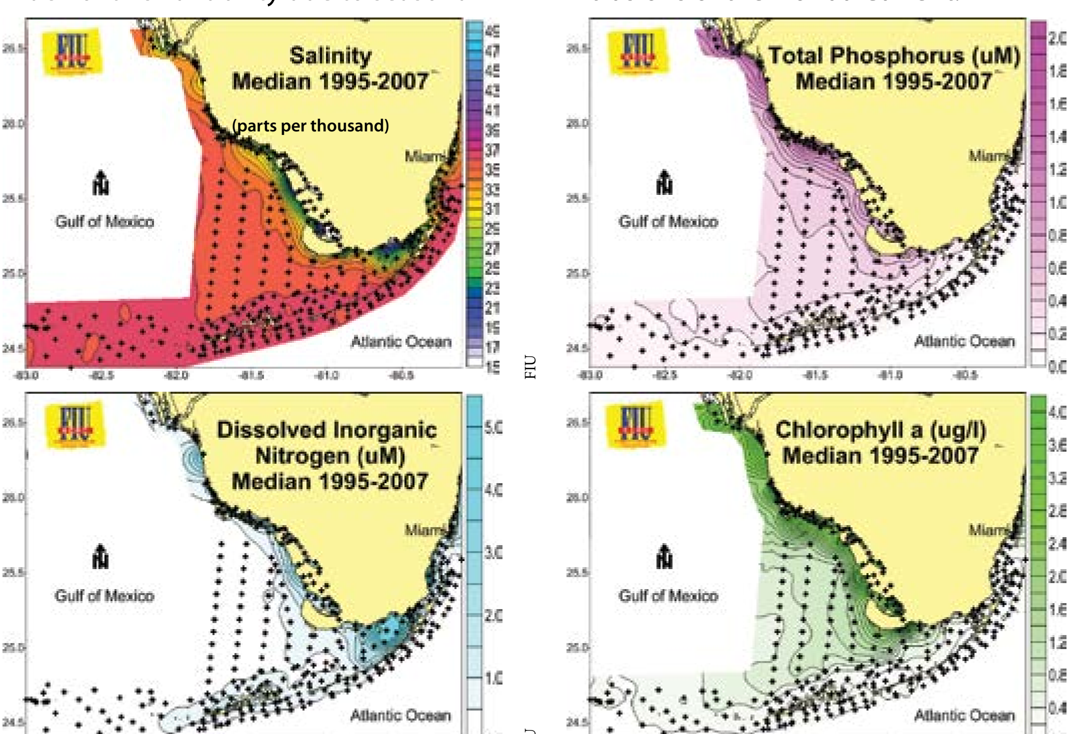
FIU

Median concentration (μM) of nitrate nitrogen (1995 – 2006) is highest (darker blue) in shallow waters on the Gulf side of the Lower Keys.

and passes. Stations located opposite channels and passes throughout the Keys had higher nutrient concentrations, phytoplankton biomass, and turbidity than those stations off islands. The area offshore Marquesas Keys exhibited the highest phytoplankton biomass (i.e., chlorophyll *a*) for any segment of the Sanctuary.

Sanctuary waters are characterized by complex water circulation patterns over both spatial and temporal scales, with much of this variability due to seasonal influence in regional circulation regimes. The Sanctuary is directly influenced by the Florida Current, the Gulf of Mexico Loop Current, inshore currents of the Southwest Florida Shelf, and tidal exchange with both Florida Bay and Biscayne Bay. Advection from these external sources has significant effects on the physical, chemical, and biological composition of waters within the Sanctuary, as does internal nutrient loading and freshwater runoff from the Keys themselves.

When the water quality of the Sanctuary is compared with data from the 175 stations sampled in the Southwest Florida Shelf, Florida Bay, Whitewater Bay, Ten Thousand Islands, and Biscayne Bay, it is apparent that the sources of water quality among the regions differ: ambient water quality in the Lower Keys and Marquesas is most strongly influenced by waters coming from the Southwest Florida Shelf; the Middle Keys by the Southwest Florida Shelf and waters from Florida Bay; the Backcountry by internal nutrient sources; and the Upper Keys by intrusions of the Florida Current.



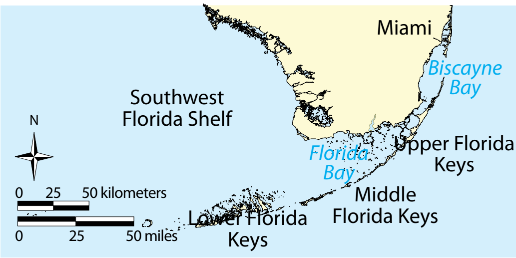
FIU FIU FIU FIU

Spatial distribution of some water quality parameters (1995 – 2007).

Water residence time is a significant driver of ecosystem structure and function in estuaries

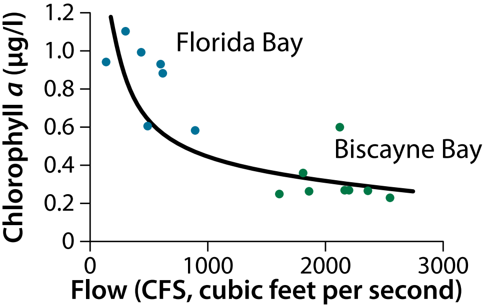
Joseph N. Boyer and Henry O. Briceño

Florida Bay is an estuary that lies between the southern tip of the Florida mainland and the Florida Keys. It covers approximately 2850 km^2 (1100 mi^2) and consists of many shallow interconnected basins, called "lakes," with an average depth of approximately 1.5 meters (5 feet). Florida Bay receives freshwater from sheet flow and creeks draining the Everglades. However, over the past century, construction of drainage canals has drastically altered the historical flow of freshwater. Because of poor flushing and high evaporation rates, portions of the Bay often become hypersaline, with salinities reaching over 40 parts per thousand (ppt). Recently, portions of Florida Bay have experienced widespread death of seagrass beds, turbid water, sustained algal blooms, and death of the sponge community.



Florida Bay and Biscayne Bay are two large estuaries in south Florida with different ecological conditions.

Biscayne Bay is the largest estuary on the southeast coast of Florida, encompassing approximately 700 km^2 (270 mi^2). It is separated from the Atlantic Ocean by a chain of islands and receives freshwater input from the Miami River and a series of smaller creeks and drainage canals along its western margin. The average freshwater flow to Biscayne Bay (121 cubic meters per second) is about 100 times the average freshwater flow to Florida Bay (1.5 m^3/s) and the rivers, creeks, and drainage canals discharging to Biscayne Bay deliver a relatively high load of nitrogen and phosphorus from adjacent urban and agricultural areas. However, even though nutrient loading into Biscayne Bay (10,203 metric tons [11,247 tons] per year total nitrogen and 24.9 metric tons [27.5 tons] per year total phosphorus) is significantly higher than loading to Florida Bay (331.7 metric tons [365.6 tons] per year total nitrogen and 3.4 metric tons [3.8 tons] per year total phosphorus), chlorophyll *a* values (plankton blooms) in Biscayne Bay are significantly lower than in Florida Bay.



FIU

Even though freshwater flow (cubic feet per second [cfs]) and nutrient loading are much higher in Biscayne Bay (green) than Florida Bay (blue), chlorophyll *a* concentration is higher in Florida Bay because of longer residence time of water (slower flushing).

Biscayne Bay has not experienced the sustained algal blooms and other dramatic ecological degradations observed in Florida Bay in recent years despite its location adjacent to a large urban area. One important reason is the difference in residence time of the water in the two estuaries. The average residence time of water in Biscayne Bay is 1 month, whereas the average in Florida Bay is 3 – 6 months. Poor internal circulation within Florida Bay due to mud banks and mangrove islands as well as reduced freshwater input result in slow turnover times of water in Florida Bay. The poor exchange of water allows increased exposure to nutrients, pollutants, and deleterious conditions that may partly explain the current conditions in Florida Bay.

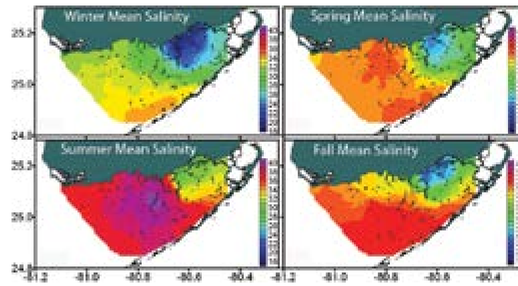
Salinity is an important variable in Florida Bay

Christopher Kelble

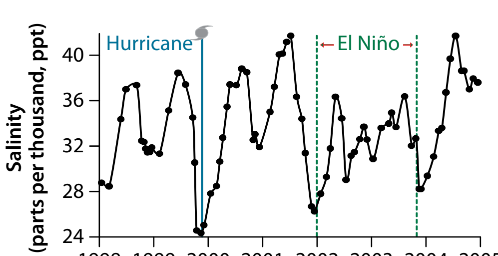
Salinity is a measurement of the concentration of salts dissolved in water. Normal seawater has a concentration of about 36 parts per thousand (ppt) total salts. When freshwater (i.e., 0 ppt) mixes with seawater in estuaries, salinity is reduced (i.e., estuarine conditions). Salinity can be used as a conservative tracer of freshwater runoff because unlike nutrients and other water quality parameters, salinity is not affected by biological processes. When evaporation exceeds rainfall or freshwater inflow, salinity can reach very high levels (i.e., more than 40 ppt), termed "hypersalinity events".

In south Florida, there is marked seasonal variation in rainfall and evaporation. When rainfall and runoff is less than evaporation, the salinity increases and reaches a maximum in early summer (June – July). Salinity decreases rapidly during the rainy months (September – December). Meteorological phenomenon, such as El Niño and tropical cyclones (i.e., hurricanes), dampen or increase, respectively, the typical annual variation in salinities.

Because of restricted circulation in Florida Bay, salinity variation is very pronounced. Florida Bay becomes hypersaline in early summer and estuarine in early winter. It is not uncommon to observe both hypersaline and estuarine conditions at different locations at the same time during intervals between those two extremes. The large salinity variations are ecologically damaging. Organisms that live in salty environments must actively regulate their interior body chemistry (i.e., osmoregulation) and have a physiological optimum of salinity, as well as minimums and maximums beyond which the organism will struggle to survive. Organisms that live in such areas either adapt to the wide fluctuations of salinity, flee when conditions become unfavorable, or die. Effects of salinity are mediated by the mobility of an organism. Sessile organisms, such as sponges, corals, and seagrasses, cannot move and are susceptible to stress and death due to unfavorable salinity conditions. Mobile organisms, such as fish, turtles, and marine mammals, can avoid localized harmful salinity conditions but may be susceptible to more widespread detrimental salinity conditions.



Mean seasonal salinities in Florida Bay, 1998 – 2005 (red indicates higher salinities, blue lower salinities).



Mean seasonal salinity distribution in Florida Bay, 1998 – 2005.

Historical water manipulation activities in south Florida have severely reduced the flow of freshwater into Florida Bay and changed the ecosystem from a predominantly estuarine condition, with a diverse seagrass community, to a more marine system, dominated almost exclusively by turtle grass. Managing water flows to reduce the severity and frequency of hypersalinity events in Florida Bay is one of the primary goals of the Comprehensive Everglades Restoration Plan.

The ecological character of Florida Bay responds to both changing climate and human activities

William L. Kruczynski, Michael B. Robblee, and James W. Fourqurean

Florida Bay is a coastal embayment found at the southern tip of Florida, downstream of the greater Everglades ecosystem. The Bay covers approximately 2850 km^2 (1100 mi^2) and is bounded on the east by the Florida Keys and open to the Gulf of Mexico along its western margin. The current ecological conditions in Florida Bay are a relatively recent development. On a geological time scale, the Earth has experienced alternating cold and warm periods. In what is now south Florida, the coral reefs that shaped the Florida Keys formed about 125,000 years ago during a warm period of elevated sea level. The last Ice Age that occurred about 28,000 years ago caused a large drop in sea level, and dry land emerged many kilometers beyond the current Bay shoreline. At that time, the area that is presently Florida Bay was vegetated by forests, freshwater marshes, and mangroves. As sea level rose over the past 5000 years, marine and estuarine waters pushed inland, flooding modern Florida Bay as recently as 1500 years ago. Changes in climate led to the development of Florida Bay, and this very young ecosystem continues to be influenced by climate and, more recently, by human activities.

SFWMD

Aerial view of Florida Bay.

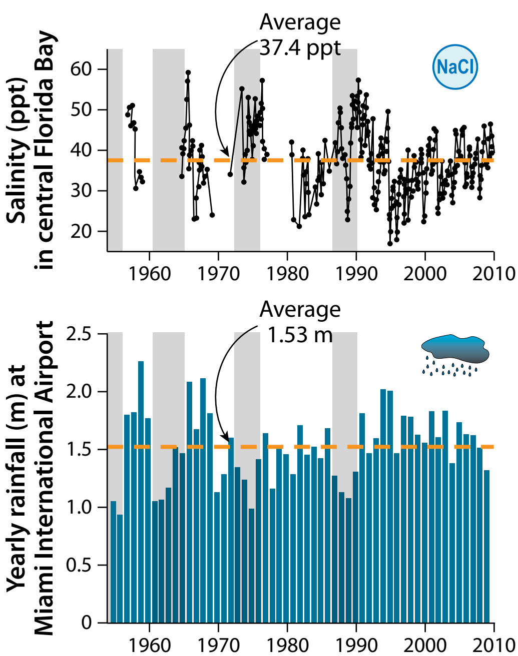
Florida Bay is a large and variable system, with mud banks enclosing shallow seagrass-covered basins or lakes in central and eastern parts of the Bay and large open water expanses in the southwestern portion of the Bay. Salinity can vary across the waterbody, with the northeastern part of the Bay influenced by freshwater runoff from the Everglades and the salinity in southwestern and western portions of the Bay maintained near that of the adjacent Atlantic Ocean and Gulf of Mexico. Since 1950, the salinity of central Florida Bay has averaged 37.4 parts per thousand (ppt). For reference, freshwater has a salinity of near 0 ppt, and open ocean water has a salinity of around 36 ppt. More water evaporates out of Florida Bay than flows into it or falls as rain, so on average, the Bay is slightly more salty than adjacent ocean waters. However, changes to inflows of freshwater can drastically alter salinity in Florida Bay. Local rainfall varies from year to year, and the salinity in Florida Bay can get much higher after a series of below average rain years and can be fresher after a series of wetter than average rain years.

T. Scott - FGS

A mud bank in central Florida Bay vegetated by mangroves and mangrove seedlings. Mud banks restrict the flow of water between adjacent basins. Plant and animal remains found in sediment cores collected from mud banks and basins provide information of historical salinity of the Bay.

Water Quality

Paleoecological investigations of the animal life and pollen buried in the muds in Florida Bay provide a glimpse into the more recent past and demonstrate that significant changes have occurred during the past 200 years. By knowing how animals and plants are currently distributed with respect to salinity, sea level, and other environmental factors, scientists can infer what the past environment was like at any point in Florida Bay by examining how the



Salinity in central Florida Bay is highly correlated with rainfall at Miami International Airport (MIA). Periods of low rainfall (shaded areas) correspond to times of high salinities in the bay.

assemblage of plants and animals changes with sediment depth; plant and animal remains are older with depth. These analyses demonstrate that Florida Bay historically had variable salinities responding to natural climate conditions that affected flows of freshwater through the Everglades into the Bay. During the late 1700s and early 1800s, salinities in Florida Bay were relatively stable and estuarine (between 20 – 30 ppt), and there were moderate amounts of submerged vegetation. From 1810 – 1892, salinities varied between 15 – 25 ppt, and the sparse aquatic vegetation present was a diverse mix of estuarine species. By the 1960s, paleoecological studies suggest that Florida Bay was dominated by plants and animals better adapted to the higher salinities of marine environments.

Available observed salinities generally support the paleoecological studies; salinities today are greater than those observed at the turn of the past century. Records from 1908 show the Bay as an estuary with salinities in the 20 ppt range and that by the late 1930s and early 1940s higher marine salinity conditions occurred. As early as 1955, extreme hypersaline conditions (i.e., 72 ppt, twice the salinity in the Gulf of Mexico) occurred in central Florida Bay and were again observed in 1991. In recent decades, hypersaline conditions (greater than 40 ppt) regularly have been present in the Bay and the end of the dry season.

Against this natural historical state of variability in salinity and ecological condition of Florida Bay, the clear connections between human alteration of the ecosystem of south Florida and conditions in Florida Bay are sometimes difficult to ascertain. The Everglades has been increasingly managed for agriculture, flood control, and water supply, with subsequent impacts to salinity conditions downstream in Florida Bay. Construction of drainage canals beginning in the 1880s, with the purpose of draining the Everglades, diverted freshwater flow to the east and west coasts of Florida and reduced flows southward into Florida Bay. The building of the Flagler Railroad (1905 – 1912) through the Florida Keys reduced the exchange of water between the Atlantic Ocean and Gulf of Mexico and increased the impact of evaporation on salinity in the interior of Florida Bay.

The shift in Florida Bay from an estuary to a marine lagoon characterized by relatively stable marine salinities but occasionally hypersaline conditions

Florida Division of Library and Information Services

Monroe County Public Library

The diversion of freshwater flow to the Everglades (left) and the construction of Flagler's Railroad in the Florida Keys (right) changed the historical flow and salinity patterns in Florida Bay.

and clear water has had biological consequences. Most notably, the seagrass community changed from a diverse mix of seagrass species to near monotypic stands of dense turtle grass (*Thalassia testudinum*). In the late 1980s, extremely high density and biomass of turtle grass, in combination with unusually high temperature and salinity conditions, precipitated the die-off of large expanses of dense seagrass in western Florida Bay. In 1991, turbidity and phytoplankton abundance increased dramatically in the Bay as nutrients were released from dead seagrasses and exposed bottom sediments. Persistent algal blooms not associated with wind events, a phenomenon not observed before seagrass die-off, characterized the previously clear Bay waters.

Concurrent declines in the shrimp harvest in the offshore Dry Tortugas fishery, for which Florida Bay functions as a principle nursery, suggest that changes in the Bay have had regional effects. Since about 1995, the region has experienced a period of stable annual average rainfall and moderate salinities, the rich seagrass beds of western Florida Bay are recovering, and the frequency of algal blooms and high turbidity events are declining.

Efforts are being made to restore the Everglade ecosystem, including Florida Bay, to a more natural state. Resource managers must be cognizant that Florida Bay varies both spatially and temporally and responds to both natural and human-caused changes in environmental conditions. Restoration planning must take into account a clear understanding of the history of Florida Bay and set defensible goals, such as reducing the frequency and magnitude of hypersaline events in central Florida Bay. Successful restoration may result in more estuarine and variable conditions, such as those that occurred in Florida Bay before the turn of the 20th century.

FDEP

The reduction of freshwater flow to Florida Bay resulted in a shift from estuarine to marine conditions and a dense, monotypic stand of turtle grass. The high density of the grass coupled with high temperature and salinity conditions resulted in seagrass die-off over large areas of Florida Bay.

There is a gradient of nutrient limitation across Florida Bay

Patricia M. Glibert and Cynthia Heil

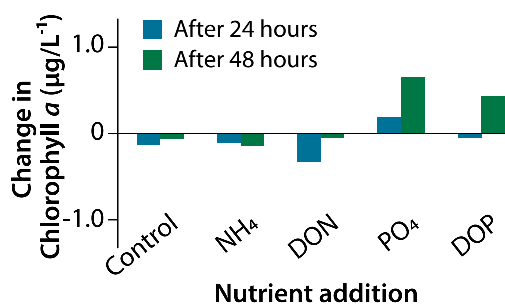
When plants do not receive the nutrients that they require, they stop growing. The nutrient in least supply, relative to the needs of the organism, is termed the "limiting nutrient." This concept was first described by Carl Sprengel and Justus von Liebig and is known as Liebig's Law of the Minimum (1840). Plants may be limited by a single nutrient, such as nitrogen, or they may be co-limited by more than one nutrient. Phytoplankton, which are free-floating microscopic plants, display nutrient limitations and, like all plants, can regulate their metabolism to improve their acquisition of the limiting nutrients.

WHOI

Alfred C. Redfield (1890 – 1983) was an ecologist before the term "ecology" was coined. He discovered that the elemental composition of planktonic organisms was consistent in ocean waters (Redfield Ratio).

All organic matter is comprised of protein, carbohydrate, lipid, and nucleic acids, which in turn are made up of the elements carbon, nitrogen, hydrogen, and phosphorus. The consistency of the relationship between elements within the plankton was first observed by Alfred C. Redfield in 1934, who found the ratio of carbon, nitrogen, and phosphorus was 106:16:1 (Redfield Ratio). Deviations in this ratio can result from the development of plankton blooms, the rapid decay, and the change from one species assemblage to another. These deviations can be used to identify potential limiting nutrients.

Florida Bay exhibits a gradient of limiting nutrients. Toward the western edge, nitrogen is the common limiting nutrient, whereas in the eastern region, phosphorus is the limiting nutrient. Nutrient limitation may develop from the depletion of the nutrient itself, as is the case for nitrogen in the western region, or from overenrichment of other elements, leading to a significant imbalance in the proportions of nitrogen and phosphorus. Phytoplankton blooms have most commonly developed in the central region of the Bay, when neither nitrogen nor phosphorus are limiting.



Typical response of algal populations in eastern Florida Bay to different nutrient additions in bioassays as measured in chlorophyll concentrations. Phosphorus limitation is indicated by the positive results of the algae to additions of phosphate (PO_4^{3-}) and dissolved organic phosphorus (DOP) additions.

There are several scientific methods to test which nutrient is limiting. One approach is called a "bioassay," where water with planktonic organisms is placed in experimental bottles and enriched with different nutrients either alone or in combination. The added nutrient that yields the greatest growth of phytoplankton in the bottles is the limiting nutrient. Using this approach, the response by the algae in eastern Bay has been found to be as much as several hundred percent after a 48-hour exposure to phosphate, whereas in western Bay, the response is also typically large to nitrogen additions.

Plankton type affects food webs

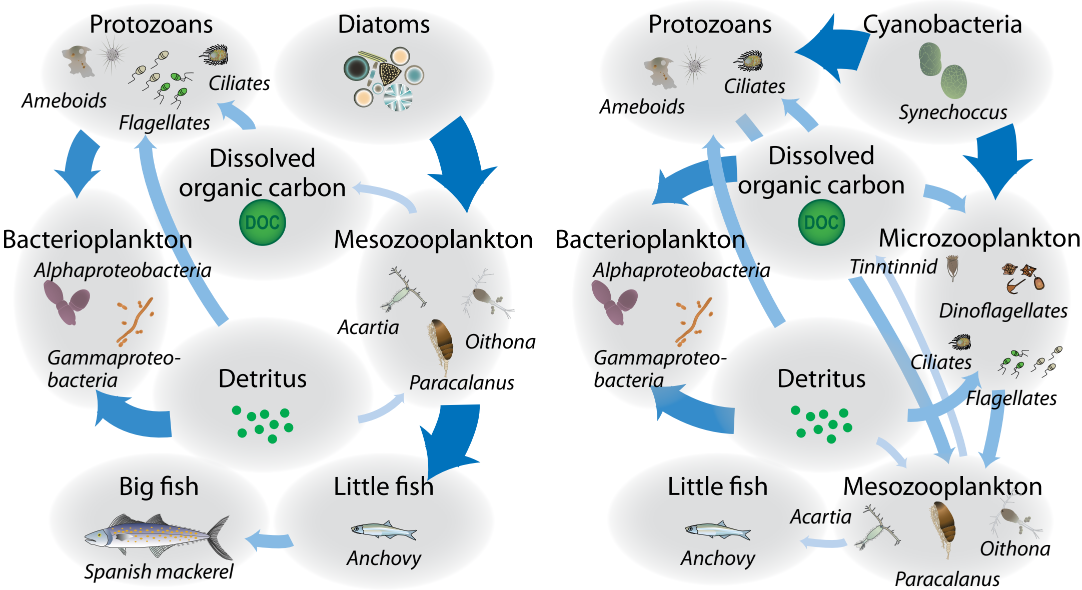
Christopher Kelble

Plants are primary producers, capturing energy from the sun and converting that energy into biological materials. Thus, plants form the base of food webs. In coastal systems, free-floating microalgae (i.e., phytoplankton) and benthic vegetation (i.e., seagrasses and macroalgae) are the primary bases of food webs, and most other organisms in the ecosystem ultimately depend on them for energy.

The planktonic food web is greatly influenced by the size, chemistry, and physical characteristics of the dominant phytoplankton species. Therefore, the type of microalgae in an area can influence the type and quantity of higher level organisms, such as fish, that are found there. In general, smaller sized phytoplankton are eaten by smaller grazers (i.e., microzooplankton) and result in smaller top level predators. The nutrient quality of the phytoplankton is also important. In large, structurally complex food webs there must be adequate quality of food in sufficient quantities.

In an ecosystem with "good" quality phytoplankton, the food web is generally less complex. The grazing community consists of larger zooplankton (i.e., mesozooplankton), sponges, and other filter feeding organisms that are then eaten by other organisms, which in turn may be eaten by larger fish. Such a "healthy" system supports larger and more diverse fish populations.

In south Florida, the dominant phytoplankton species in blooms, excluding harmful algal blooms, such as toxic red tides (*Karenia brevis*), are either small sized cyanobacteria, such as *Synechococcus*, or large diatoms. These two phytoplankton groups support significantly different food webs: the larger diatoms support healthy, large fish populations, and the cyanobacteria support a low quantity of smaller fish.



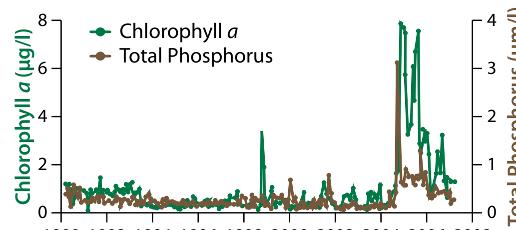
A healthy aquatic ecosystem (left) is based on a diverse mix of large phytoplankton that results in a healthy fish community. An aquatic ecosystem based on a single, overabundant species of smaller phytoplankton (right) results in a less diverse fish community dominated by smaller fish species.

An unprecedented phytoplankton bloom occurred in eastern Florida Bay from 2005 – 2008

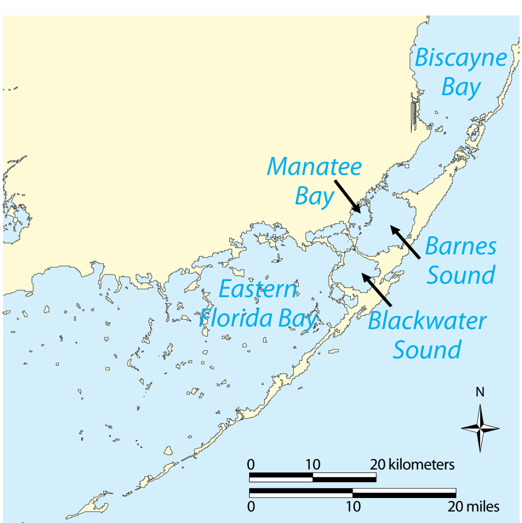
David T. Rudnick, Stephen P. Kelly, Christopher J. Madden, Kevin M. Cunniff, Joseph N. Boyer, and Stephen Blair

Eastern Florida Bay is an unusual region in an unusual estuary. The majority of estuaries receive most of their nutrients from their terrestrial watersheds, and this nutrient delivery, combined with light availability, largely determines the amount of phytoplankton (microalgae in the water) in the estuary. However, in Florida Bay, most freshwater runoff from the Everglades watershed flows into the eastern bay, and this runoff has very low concentrations of the nutrient most limiting productivity, phosphorus. This low nutrient input, combined with the presence of seagrasses that compete for phosphorus and sediments that chemically bind phosphorus, inhibits the growth of phytoplankton in the eastern Bay.

These shallow waters typically have phytoplankton abundance more similar to the open ocean than estuaries – the waters are a low nutrient "desert." More than 15 years of water quality monitoring in eastern Florida Bay documented that concentrations of chlorophyll *a*, an indicator of phytoplankton biomass, and total phosphorus were lower than almost anywhere else in coastal south Florida. That changed in the fall of 2005.



Time series of water column phosphorus (brown) and chlorophyll *a* (green), an indicator of algal biomass, in Barnes Sound located south of Biscayne Bay. The phytoplankton bloom was preceded by a large increase of phosphorus in the water column.



Map of eastern Florida Bay and southern Biscayne Bay, where a microalgal bloom occurred from 2005 – 2008.

An unprecedented bloom of cyanobacteria (a high abundance of microalgae) occurred over much of eastern Florida Bay and southern Biscayne Bay beginning in November 2005, 1 month after regional phosphorus concentrations were more than 10 times higher than typical concentrations. This exceptionally large amount of phosphorus almost certainly caused the initiation of the regional cyanobacteria bloom. What is uncertain is the source of this phosphorus and, to a lesser extent, how the bloom could persist for 3 years (2005 – 2008) in this low nutrient environment. Two hypotheses have been developed to explain the initiation of the bloom: phosphorus inputs from stormwater from hurricanes and phosphorus inputs from road construction activities.

The timing and spatial distribution of the cyanobacteria bloom provide clues about the source of the phosphorus and the cause of the bloom. The bloom first occurred at a relatively small scale in two basins east of U.S. Highway 1 (Manatee Bay and Barnes Sound) in September 2005, immediately after the passing of

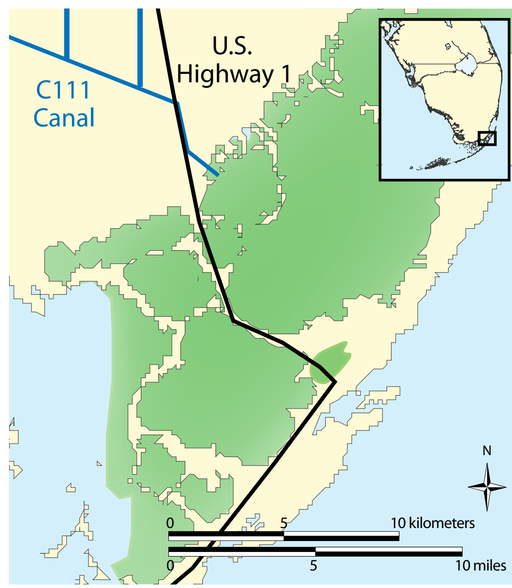
NOAA

In September 2005, Hurricane Rita passed over south Florida and provided substantial amounts of rainfall to the region that may have contributed to the release of phosphorus to surface waters of eastern Florida Bay.

Hurricane Katrina in late August. The bloom then expanded to a regional scale in November, after the passing of two more hurricanes, Rita in late September and Wilma in late October 2005.

The timing of the bloom is consistent with the hypothesis that these three successive hurricanes initiated the bloom. A spatial clue about the cause of the bloom was that the highest chlorophyll *a* concentrations consistently occurred adjacent to U.S. Highway 1. For about 3 years, the bloom occurred on both sides of the highway, especially near Key Largo. This spatial distribution points to the possibility that a large highway construction project that started in the spring of 2005, widening the road from the Florida mainland to Key Largo, was also a cause of the bloom.

Nutrient inputs occurred in association with both U.S. Highway 1 construction and the fall 2005 hurricanes, but the amount from every potential source cannot be estimated reliably. To widen the road bed, adjacent dense stands of mangrove trees were cut, mulched, and mixed into the peat soil along with cement to stabilize the road base. Mulching and burial of this fresh organic matter, including roots, along with disturbance of the soil organic material likely resulted in a release of nutrients



A large phytoplankton bloom persisted in eastern Florida Bay and southern Biscayne Bay from 2005 – 2008. The extent of the bloom shown is for 2006 – 2007.

through microbial decomposition processes to the surrounding waters. The amount of phosphorus released by construction activity is difficult to estimate but was likely a small component of the approximately 19 metric tons (21 tons) of phosphorus required to account for the regionally elevated phosphorus observed in October 2005. The leaves and wood of mulched mangroves probably only contained about 1 metric ton (1.1 ton) of phosphorus, whereas the soils and

H. Carman - SFWMD

Construction along U.S. Highway 1 from the Florida mainland to Key Largo in 2005 disturbed organic soils that may have resulted in the release of phosphorus to adjacent waters.

roots contained an unknown amount of phosphorus.

Hurricanes cause broad and strong disturbances of ecosystems, and release and transport of nutrients are part of this disturbance. One major nutrient source affected strongly by Hurricane Katrina was nutrients stored in soils and waters of the developed portion of the adjacent south Florida watershed. With Katrina, heavy rainfall (15 – 30 centimeters [6 – 12 inches]) fell in the region, and in the process of protecting residential and farming areas from flooding, stormwater was released into Manatee Bay via the C-111 Canal. With this stormwater, approximately 2.6 metric tons of phosphorus was transported toward Manatee Bay and Barnes Sound.

However, the phosphorus observed in late August does not account for the regionally elevated phosphorus found in October, nor does it come close to the estimated 19 metric tons (21 tons) required to account for the regionally elevated levels of phosphorus. Other sources of phosphorus that could have been mobilized and transported by high winds, waves, and storm surge due to hurricanes were nutrients from the Everglades, the Florida Keys, and the Bay itself. This includes releases of nutrients from wetland leaves and soils, seagrass leaves, Bay sediments, and groundwater. The exact quantity of these potential nutrient inputs in the fall of 2005 is unknown.

Neither of the hypothesized causes of the initiation of the cyanobacteria bloom (hurricanes and road construction releases) is fully consistent with the timing and characteristics of the bloom. Road construction and mangrove mulching began months before the bloom started. Many hurricanes had passed over or near Florida Bay during previous decades without the occurrence of phytoplankton blooms in this location. This includes releases of stormwater from the C-111 Canal that were similar to the quantity of water and phosphorus released with Katrina. Yet, no previous water releases

H. Carman - SFWMD

The phytoplankton bloom is visible on the Manatee Bay side of the C-111 Canal terminal water control structure, S-197. This structure is opened to provide flood control during periods of high rainfall. There was a large release of water during Hurricane Katrina, which may have initiated the plankton bloom.

were followed by blooms in the region.

It is likely that both hypothesized causes contributed to the initiation of the cyanobacteria bloom and, furthermore, may have been interactive. One such interaction may have been the movement of materials from the construction site by the rain, wind, and waves of the hurricanes. Another possibility is more complex: that dissolved organic material leaching from the construction area had been decomposing in adjacent waters, with elevated demand for dissolved oxygen, at the time of the hurricanes. Large areas with low dissolved oxygen concentrations were measured following Hurricane Katrina, likely in association with dissolved oxygen uptake as well as with stratification of the water column after heavy rainfall and runoff. Such a low dissolved oxygen scenario following Hurricane Rita, another wet storm, could have spurred chemical and biological releases of phosphorus from the sediments.

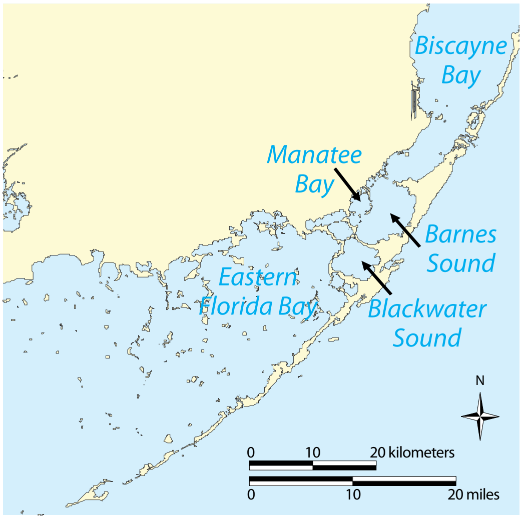
Regardless of its cause, the cyanobacteria bloom spurred a chain of events, including seagrass mortality, that helped to sustain the bloom for 3 years. The occurrence of this exceptional phytoplankton bloom demonstrated the extreme sensitivity of eastern Florida Bay to phosphorus availability and how rapidly the structure and function of an ecosystem can change.

Phytoplankton blooms can be self-sustaining and alter benthic communities

David T. Rudnick, Stephen P. Kelly, Amanda A. McDonald, and Christian L. Avila

An unprecedented phytoplankton (i.e., water column microalgae) bloom began in eastern Florida Bay and southern Biscayne Bay in the fall of 2005 and was sustained over a 3-year period. Bloom initiation was likely the result of disturbance from three consecutive hurricanes combined with road construction along U.S. Highway 1 that began in early 2005. Increased phosphorus availability was likely the key factor that initiated the bloom. Both the occurrence and the longevity of the bloom were surprising, given that this region of Florida Bay previously had very low nutrients and no recorded history of phytoplankton blooms.

To sustain such a phytoplankton bloom, cell population losses (to grazing, sinking to sediments, and export via currents) must be less than or equal to cell population gains (through growth and reproduction as well as through the import of cells via currents). A key factor enabling cell gains is the continuing supply of nutrients (both phosphorus and nitrogen). In the case of the bloom in eastern Florida Bay and southern Biscayne Bay, once the bloom began, little phosphorus was supplied from external sources; the bloom appeared to be supplied from local, internal sources of nutrients. Furthermore, the existence of the bloom created a set of circumstances that resulted in enhanced nutrient availability.



Map of eastern Florida Bay to southern Biscayne Bay, where a persistent phytoplankton bloom occurred from 2005 – 2008.

C. Avila - Miami-Dade County DERM

Cyanobacteria bloom in Barnes Sound on December 21, 2005. The cells of such blooms absorb light, greatly decrease light penetration to the bay bottom, and decrease productivity of submerged aquatic vegetation.

This scenario of a self-sustaining phytoplankton bloom involved the loss of two major ecosystem components: submerged aquatic vegetation and sponges. The loss of submerged aquatic vegetation and sponges affected the entire food web of the ecosystem because they provide habitat for a diversity of fish and invertebrates. Another effect of sponge mortality in the region of this bloom was probably a decrease in sponge grazing on bloom organisms. These effects of the phytoplankton bloom, and the associated cycle by which the bloom was sustained, are not unique to this bloom and has been observed in other estuaries.

The loss of submerged aquatic vegetation is a critical part of the cycle sustaining the phytoplankton bloom. A decrease in submerged aquatic vegetation cover in the region was measured after bloom initiation in the fall

Clear water is required for healthy growth and productivity of submerged aquatic vegetation (left). Submerged aquatic vegetation cannot be sustained and dies when not enough light reaches the bottom, such as during prolonged phytoplankton blooms (right).

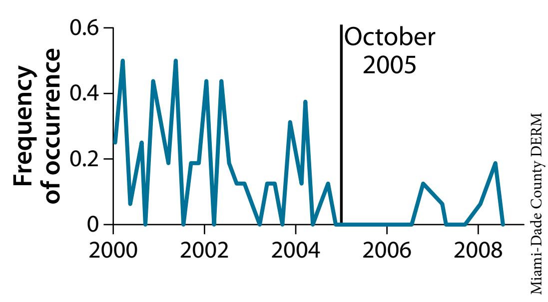
of 2005. This loss was most pronounced in Barnes Sound and Blackwater Sound: the basins where the bloom was most intense and persistent. Furthermore, the loss was greatest in the deepest waters of these basins. A likely mechanism responsible for the mortality of submerged aquatic vegetation was a decrease in light penetration through the water column to the bay bottom, decreasing submerged aquatic vegetation photosynthesis. Such shading of the bottom by phytoplankton blooms, with consequent mortality of submerged aquatic vegetation, commonly has been observed in shallow estuaries worldwide. In the case of this

In 2005 – 2006, sponges found throughout the bloom area probably died as a result of high cyanobacteria concentrations and low dissolved oxygen.

region of Florida Bay and Biscayne Bay, other factors may also have affected submerged aquatic vegetation, including decreases in salinity and low dissolved oxygen concentrations causing lethal hydrogen sulfide toxicity following Hurricanes Katrina and Rita.

Regardless of the exact cause, once submerged aquatic vegetation mortality began, a cycle (i.e., feedback loop) began that increased nutrient availability, sustaining the bloom and further harming surviving submerged aquatic vegetation. Available nutrients in the water column increased from several processes: the decomposition of dead submerged aquatic vegetation, a decrease in benthic nutrient uptake (with the loss of submerged aquatic vegetation), and the nutrient releases associated with the destabilization of sediments due to the loss of sediment binding by seagrass roots. Sediment destabilization also increased the amount of sediment suspended in the water column, decreasing light penetration and further propagating this destructive cycle.

Another contributing factor regarding the maintenance of the phytoplankton bloom is the physical nature of the estuaries and the efficiency of nutrient cycling. Although water can flow rapidly through typical riverine estuaries, Florida Bay and the southern portion of Biscayne Bay have diffuse inputs of freshwater flow that are small relative to the volume of the systems. Consequently, water in the bloom region has a very long residence



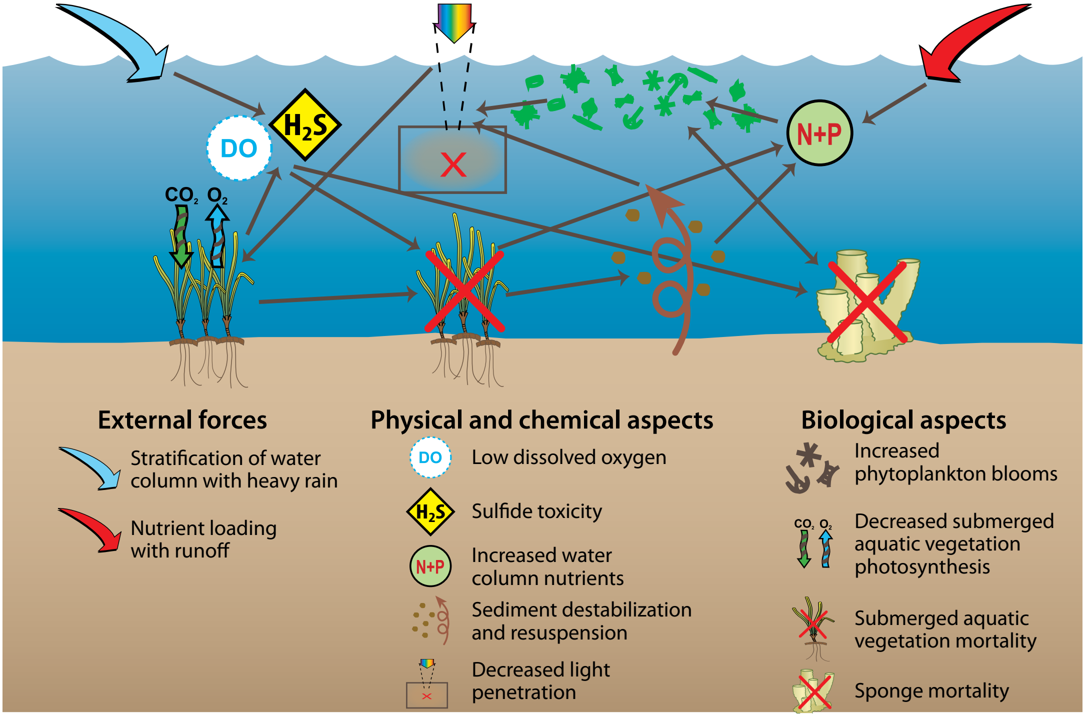
Sponge occurrence in Blackwater Sound decreased significantly in October 2005 (marked by vertical line) following the initiation of the phytoplankton bloom.

time that results in the retention of phytoplankton cells and phosphorus. This, combined with highly efficient phosphorus cycling, enabled the bloom to thrive on an initial input of phosphorus and nutrients released with the death of submerged aquatic vegetation.

The loss of sponges may also have been a factor in sustaining the bloom. Although sponges were not as common in this area of Florida Bay as in the Middle Florida Keys, they became extremely rare by 2005. The loss of sponges may have been caused by multiple factors, including decreased salinity following rainfall and runoff from hurricanes and low dissolved oxygen observed after Hurricane Katrina. It is also possible that sponge mortality was caused by the bloom itself. Sponges feed by filtering small organisms from the water column, including the dominant bloom organism, a cyanobacteria (blue-green algae) species. At low cell abundance, such filtration can slow the population growth of the cyanobacteria (a top-down control of bloom). However, at the high cell abundance of a bloom, sponge growth can be inhibited, and sponges can die, likely from clogging of their internal flow channels. With sponge mortality, grazing on bloom organisms decreased, helping to sustain the bloom.

The most likely reason why the bloom observed in eastern Florida Bay and southern Biscayne Bay lasted longer than blooms observed in other portions of Florida Bay may be the relatively low flushing characteristics in these regions.

A lesson learned from the dynamics of this bloom is that an ecosystem can quickly and readily reach a tipping point, where it changes state from one dominated by seagrass with clear water to one dominated by a sustained phytoplankton bloom with opaque, green water.



Conceptual model showing how phytoplankton blooms in eastern Florida Bay and southern Biscayne Bay were sustained through feedback loops among ecosystem components. Water column stratification due to heavy rains during hurricanes and nutrient loading from runoff are external forces affecting the ecosystem. Heavy phytoplankton growth decreases light penetration to seagrasses and clogs sponge filter mechanisms. Low dissolved oxygen due to water column stratification results in sulfide toxicity that can kill seagrasses and sponges. Death of seagrasses destabilizes sediments, which increases turbidity, and results in the release of nutrients from sediments and decomposing seagrasses.

Blackwater events can occur when unusual environmental conditions exist

Cynthia Heil

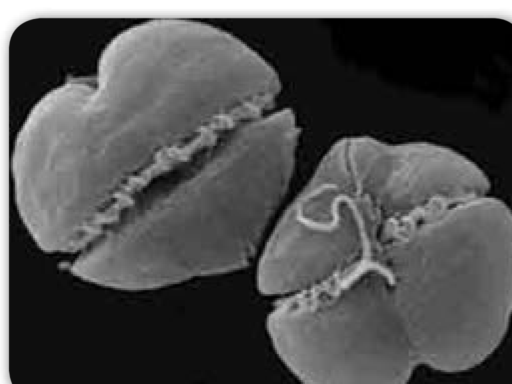
In January 2002, fishermen and pilots of small aircraft observed an area of dark colored water on the Southwest Florida Shelf, west of the Everglades, that they called "blackwater." They reported to the media that the waters were devoid of life. This shallow water area to the northwest of Florida Bay is characterized by extensive seagrass beds and a productive stone crab fishery. It receives freshwater inputs from both the Shark River in the Everglades and larger rivers to the north, including the Caloosahatchee. Much publicized in the popular press at the time, the 2002 blackwater event was not the first report of this type of event; a similar event was reported in 1898.

NASA

A 2002 blackwater event northwest of Florida Bay.

Investigations revealed that the blackwater area was not lifeless; in fact, a large algal bloom was present, consisting of a mix of nonharmful diatoms and a toxic dinoflagellate, *Karenia brevis*. *Karenia brevis* is responsible for Florida red tides. Also present in the bloom were high concentrations of comb jellyfish (i.e., ctenophores). Scientists believe that the blackwater event was caused when several different biological, chemical, and physical events co-occurred. A declining red tide event that occurred on the Southwest Florida Shelf was carried south at the same time that a seasonally occurring diatom bloom was shifted to the northwest. Using satellite imagery, scientists were able to trace the water mass containing this bloom back to an area to the north, where river waters containing both nutrients and high concentrations of dissolved tannic material supported the bloom and caused the dark colors of the water. The presence of high concentrations of comb jellyfish indicates that normal food chains were disrupted within the bloom. The mass of water containing the bloom was caught in a local area of stagnant circulation (i.e., an eddy), which kept it from being dispersed for a 3-month period. Also, unusual climate extremes were occurring in southwest Florida, including a severe drought followed by fewer and less severe winter fronts that could have dissipated the eddy.

The 2002 blackwater event had a large impact on corals, sea fans, and sponges as it passed the Lower Keys. Two coral reefs north of Key West experienced a 70% decrease in stony coral cover, a 40% reduction in coral species, and the near elimination of sponges.



FWC

Karina brevis is a toxic dinoflagellate that causes red tides in the Gulf of Mexico from Texas to Florida and along the Atlantic coast as far north as North Carolina. Red tides are characterized by discolored water, dead fish, and toxic aerosols that cause respiratory irritations. Cell size is approximately 30µm (0.001 in).

Algal blooms vary in type, size, and effect

Nancy Diersing

What organisms cause algal blooms?

Algal blooms are caused by photosynthetically-active organisms (phytoplankton) that are suspended in the upper sunlit layer of waterbodies. Phytoplankton is commonly composed of microalgae, which are microscopic plants, or a type of bacteria (cyanobacteria) that is commonly called "blue-green algae." Bloom organisms often discolor the water because of the pigments found in their cells.

What causes a bloom?

Under the right conditions of sunlight and nutrients, phytoplankton cells can grow and reproduce faster than losses due to grazing, death, sinking, or advection out of the region. Sometimes blooms are composed of one dominant species, while at other times they are comprised by many species. Cell concentrations in blooms may reach millions of cells per milliliter.

What nutrients are important?

Phytoplankton obtain nutrients needed for growth and reproduction from the water. Macronutrients, including nitrogen and phosphorus, promote growth. Vitamins and trace metals (e.g., iron, zinc, manganese) are also needed in small amounts. Excessive nutrient loads promote excessive growth.

Why are some blooms more serious than others?

Blooms may be "harmful" through direct or indirect impacts and can become long-term events that can affect the entire ecosystem. Blooms produce oxygen during the day but use oxygen during the night. The result can be lower oxygen levels in the water, harming other organisms and even leading to fish kills. Some bloom organisms contain toxins. People who eat shellfish from waters experiencing a toxic bloom can become very ill, and the toxins can affect a variety of marine organisms. Harmful algal blooms have economic and cultural implications, especially in coastal communities that depend on tourism and harvesting of seafood.

How do blooms affect the ecosystem?

Phytoplankton form the base of many food webs and are fed upon by small grazers. Any significant change in the base of a food web that affects these small grazers also affects the fish, birds, and other animals in that food web. In addition, bloom organisms can become so dense that they physically block the pores and channels of some filter feeders, such as sponges, leading to their death. Dense blooms can also block the transmittance of light to benthic macroalgae and to seagrasses, causing their decline.

How do cyanobacterial blooms differ from other algal blooms?

Many of the impacts of cyanobacterial blooms are similar to those of other algal blooms. They can disrupt ecosystem food webs, and some are toxic. One of the most common cyanobacterial bloom species in Florida Bay is *Synechococcus elongatus*.

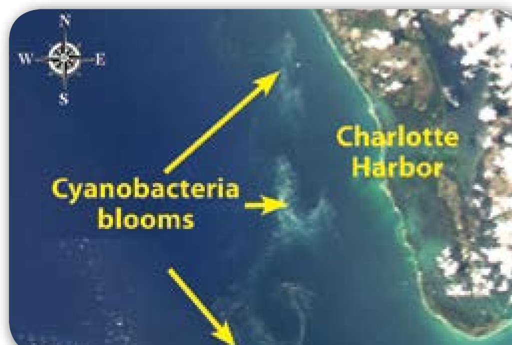
What caused the blooms in central and northern Florida Bay in the early 1990s?

A complex series of factors that are still not completely understood were responsible for blooms. It is believed that the blooms were sustained by nutrients that were released to the water column from the death and decomposition of many hectares of turtle grass and from the sediments that were no longer stabilized by seagrass roots. The resulting nutrient and light conditions, in conjunction with low flushing rates, favored the growth of *Synechococcus*.

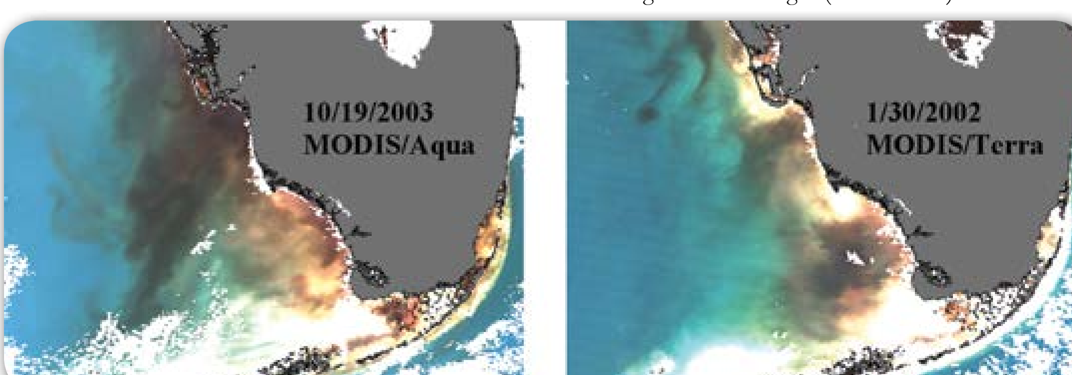
South Florida marine environments can be assessed with satellite remote sensing

Chuanmin Hu

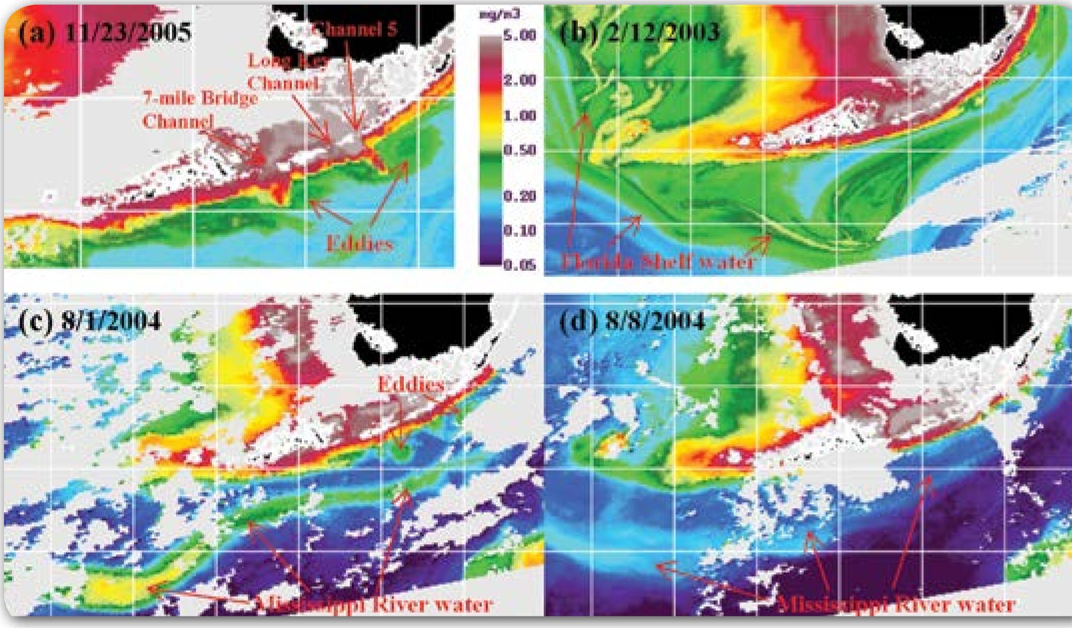
Compared with other means to collect oceanographic data, remote sensing from operational satellite instruments, such as Advanced Very High Resolution Radiometer, SeaWiFS (Sea-viewing Wide Field-of-view Sensor), and Moderate Resolution Imaging Spectroradiometer (MODIS), provides frequent (daily) and synoptic (same time) measurements of the ocean surface properties in near real time. These properties include sea surface temperature and ocean color (reflected solar light) as well as other properties derived from ocean color, including water clarity and turbidity, abundance of algae suspended in the water column, and concentrations of other suspended and dissolved materials. In some areas, these remote measurements may not be as accurate as shipboard measurements. However, they provide critical and timely information to study water quality events, monitor pollutants, help guide ship surveys, reveal connectivity between different ecosystems, validate numerical circulation models, and to assess the long-term coastal changes to help manage the coastal ecosystem. Indeed, satellite remote sensing is an indispensable component in any ocean observing system around the world because of the wide coverage and near real-time data availability. A few examples are shown here to illustrate how satellite remote sensing can be used to study and monitor the south Florida coastal ecosystem.



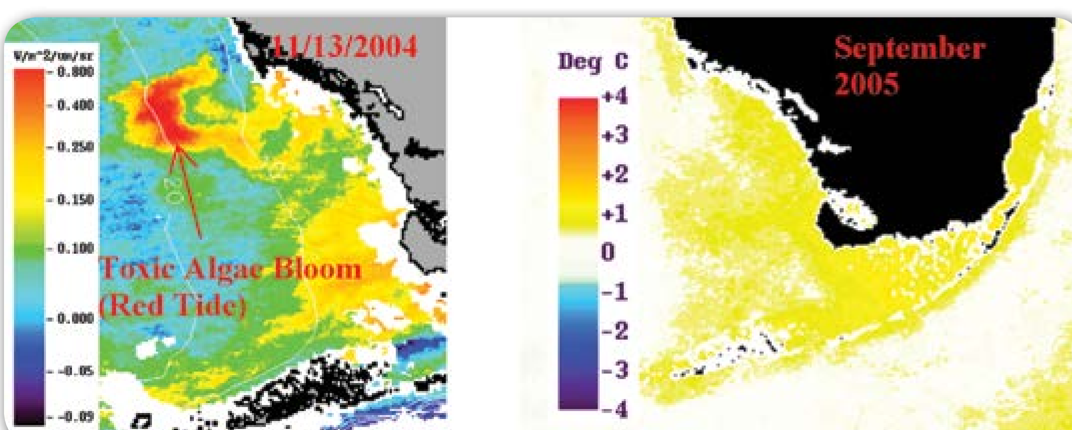
Red-Green-Blue MODIS image on May 23, 2004, showing blooms of the blue-green algae *Trichodesmium* spp. off Charlotte Harbor. The algae can fix nitrogen from the air, providing nutrients to other organisms, including the red tide algae (*Karenia brevis*).



Enhanced Red-Green-Blue MODIS images showing two examples of how the south Florida ecosystem is connected. The darkish colors resulted from light absorption by high concentrations of phytoplankton and/or dissolved materials in the water. White colors represent clouds, shallow water, or high turbidity. The "blackwater" patch on January 30, 2002 (left) is a result of earlier red tides drifting south, emanating from the north and runoff from rivers draining the Everglades. The timely detection of the blackwater event by satellite remote sensing helped coordinate ship surveys, which found toxic and nontoxic algae in the dark waters. This is the longest blackwater event in history (more than 3 months) and it resulted in significant benthic decline (die-offs of sponges and corals) in the Lower Keys. The dark water plume on October 19, 2003 (right) is due to excessive rainfall that led to higher than normal river discharge from the Caloosahatchee and Peace Rivers into Charlotte Harbor.



MODIS images showing how the south Florida marine ecosystem is affected by water from various sources. The images are color coded to show the phytoplankton abundance (through chlorophyll *a* concentrations in milligrams per cubic meter). Because of the difficulty of sensors separating the reflectance from the water column and benthic communities in shallow waters, the values for Florida Bay and other shallow waters may not be as accurate as for deeper areas; however, the emphasis here is on the spatial patterns. Image a, Intrusion of Florida Bay waters through the narrow tidal pass channels to the Atlantic side of the Florida Keys. Image b, Waters from the Southwest Florida Shelf entering the Florida Straits. Image c, Mississippi River water in the Florida Straits. Also shown are the 12-mile wide eddies near the Keys. These eddies play important roles in fish larvae transport and survival as well as in nutrient supplies. Image d, Mississippi River water diluted in the Florida Straits. It was estimated that about 23% of the entire Mississippi discharge between July – September 2004 entered the Florida Straits, equivalent to 4 times the volume of Lake Okeechobee.



Two examples of how satellite images are used to monitor the environmental health of the Southwest Florida Shelf. Left, MODIS image showing a toxic red tide bloom. The bloom is revealed by the solar-stimulated fluorescence (glow) of the algae under sunlight. Red color shows high algae concentrations. Red tides are known to kill fish and marine mammals. Right, Sea surface temperature anomaly. Portions of the Southwest Florida Shelf, Biscayne Bay, Florida Bay, and the Florida Keys were 1.0°C warmer than usual between August – September 2005, after which some degree of coral bleaching occurred at several reef sites in the Florida Keys.

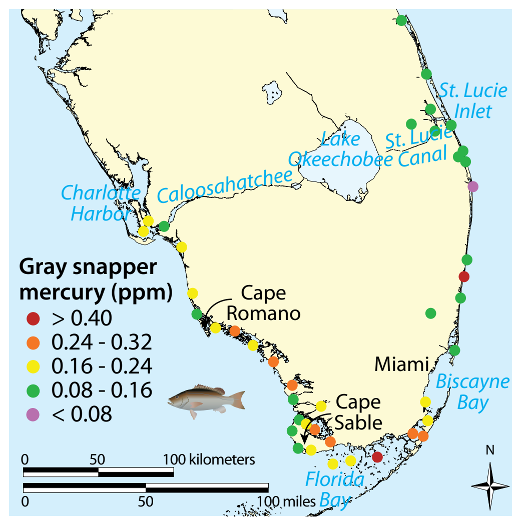
Mercury is a global contaminant with local impacts

Darren G. Rumbold and David W. Evans

Mercury is a globally dispersed contaminant and, thus, a global problem; however, localized "hot spots" can develop where local conditions favor accumulation through food webs (i.e., biomagnification). The Florida Department of Health has issued guidance advising the public to limit consumption of 59 species of commercially and recreationally valued fish from coastal waters off Florida because of the amount of toxic mercury contained in the fish flesh. Ongoing monitoring in the south Florida coastal marine environment has identified several hot spots or local regions where fish have higher mercury concentrations than surrounding areas. Fish consumption advisories are not unique to Florida. According to the United States Environmental Protection Agency (2007), 48 states, one territory, and two tribes have issued mercury advisories; 12 states, including Florida, have statewide advisories for mercury in coastal waters.

Mercury is a naturally occurring metal mobilized through various geologic processes, such as volcanic activity and the weathering of rock. Mercury mining and industrial processes, such as metal smelting and coal combustion, augment the amount available through natural processes. Although wastes from mining and chemical processing are no longer major direct sources to waterways in the United States, deposition of mercury released to the atmosphere, both in the United States and elsewhere, provides a continuing source. Mercury deposited on the landscape from past human activities also provides an ongoing source to fish.

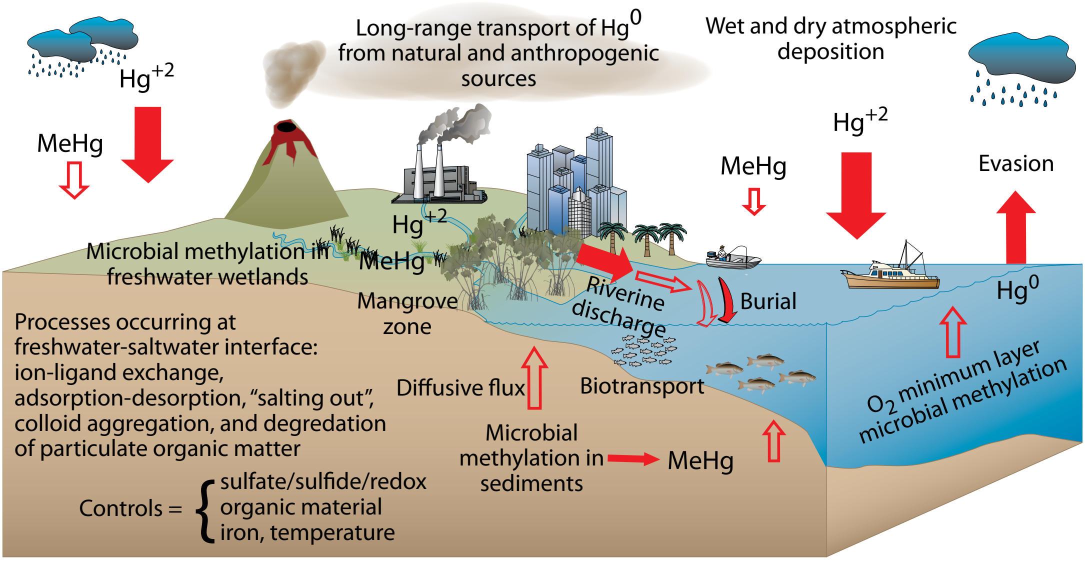
Mercury cannot be destroyed or biodegraded. Instead it cycles among the different environmental media—air, water, soil, and biota—often taking on different chemical forms as it cycles. This determines the amount of time mercury resides in each medium and the concentration it achieves in each. Elemental mercury (symbolized as Hg0) can remain in the atmosphere for up to a year and can be globally dispersed before falling back to Earth. By comparison, the mercuric ion (Hg^{2+}) is more reactive, spending only hours or days in the atmosphere. It often deposits closer to its emission source. Hence, local deposition depends on both global and local emission sources.



D. Evans, unpublished data

Map showing mercury levels in gray snappers collected from coastal waters of south Florida.

In south Florida, atmospheric deposition is the leading source of mercury. During the 1980s and early 1990s, emissions from local municipal solid waste incinerators were believed to dominate over global background sources. These emissions have declined, but medical waste incinerators may be a new local source. Equally important, the omnipresent mercury deposition from the global atmospheric pool continues and may increase in the future. Currently, 12% of the emissions to the global pool are believed to originate from a single province in China (Guizhou), where mercury and coal, which always



General conceptual model showing sources, transport, and cycling of inorganic mercury (solid red arrow) (e.g., Hg0, Hg^{2+}) and methylmercury (open red arrow) (MeHg) to the marine environment.

contains some mercury (more so if found near mercury deposits), are mined and processed near each other. This source may increase as China uses more coal. Thus, efforts to reduce local mercury deposition through local emission controls have limited effects.

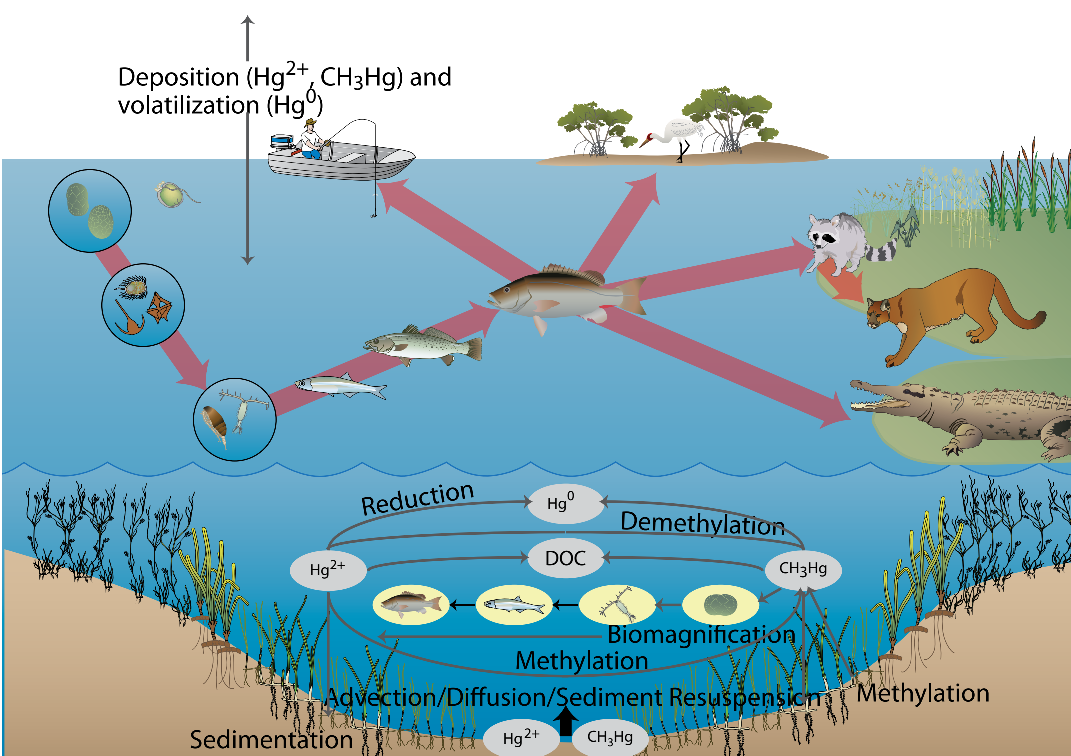
The form of mercury that is globally dispersed is of limited toxicological risk. However, if after deposition it is taken up by bacteria, in particular sulfate-reducing bacteria, this inorganic mercury (e.g., Hg^{2+}) can be transformed by the addition of a methyl group (i.e., methylation) as an incidental byproduct of the normal metabolism for the microbe. It is the amount of mercury present in this methylated form in sediment and water, not the total amount of mercury present, that is the critical factor in determining whether a given system will have a mercury problem. The trace amounts of both inorganic mercury and methylmercury in water (usually less than one part per trillion in the case of methylmercury) are not toxic if the water is ingested. Yet, methylmercury can reach harmful levels in the living biota due to its accumulation in food webs. Biomagnification is the stepwise increase in concentration in each successive level of the food web (e.g., plants < herbivores < predators) as each feeds on and accumulates the mercury accumulated in the trophic level below.

Methylmercury exposure can produce an array of toxic effects. Its most insidious effect is neurotoxicity to fetuses exposed while in the womb (i.e., in humans and other mammals). Children exposed while in the womb may show signs of mild cognitive dysfunction, and the development of cerebral palsy-like symptoms may develop. Fish-eating wildlife suffering even a mild dysfunction have reduced survival fitness through reduced competitive abilities and a greater risk of predation.

Much has been learned about the biogeochemical cycling and fate of mercury in freshwater systems, especially from research conducted in the Florida Everglades. In marine systems, much less is known about mercury cycling and its fate despite the knowledge that marine fish are the main source of methylmercury exposure in humans. There is a need to determine where methylation is occurring and what are the dominant sources of inorganic mercury that are being transformed into methylmercury.

The mangrove ecotone, which in south Florida often serves as the transition between terrestrial-freshwater and marine systems, can be an important site for methylation. Yet, a lingering downstream impact from the freshwater system is suggested in the pattern of spatial variability observed in the mercury levels in fish collected from bays along the south Florida coast. Fish from mangrove-fringed bays associated with large, wetland-containing watersheds often show higher mercury levels, suggesting that some of the methylmercury produced in the freshwater system is transported across the landscape. In Florida Bay, this was confirmed by measuring methylmercury in the water flowing down creeks into northeast Florida Bay. However, methylation of inorganic mercury also occurs in sediments of the outer bay that have nearly full strength seawater. Hence, there is a need to continue to monitor fluxes of inorganic mercury to the marine environment in order to determine the relative importance of various sources. Targeted source control is one means of reducing the toxicological impact of mercury.

In addition to inorganic mercury loading, many complicated and numerous geochemical and biological factors play a role in controlling the rate of net methylation in the receiving system. The carbon and sulfur cycles are always at the center of these biogeochemical reactions. In freshwater systems with abundant carbon, sulfur typically is limiting. In marine systems with abundant sulfur, organic matter can be limiting. Untangling these different processes and fluxes to determine which drives methylation and biomagnification is difficult in the estuaries because all are greatly influenced by hydrodynamics. Each estuary differs in its hydrodynamics with both temporal and spatial variability that comes with daily tides and seasonal changes in rainfall and runoff.



Adapted from https://www.usgs.gov/themes/factsheet/146-00/

Mercury is a toxic contaminant that is globally dispersed and can be biomagnified in aquatic food chains.

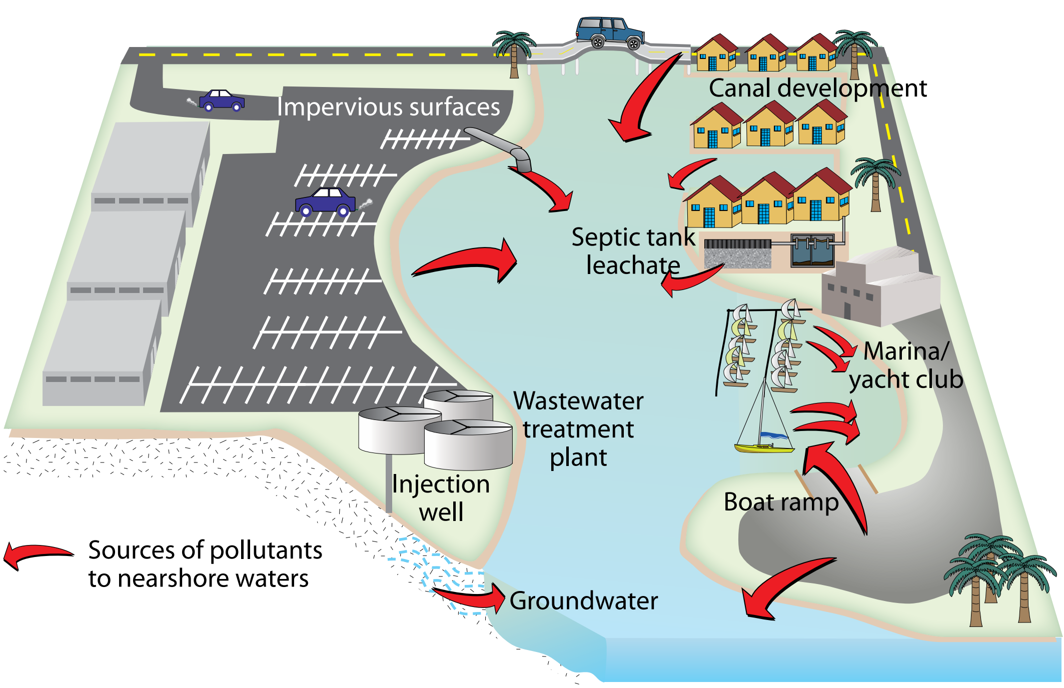
Water pollution in the Florida Keys comes from many different sources

Gus Rios, William L. Kruczynski, and George Garrett

The economy of the Florida Keys is directly linked to clean water and a healthy ecosystem. Because of the increasing population and developmental pressures experienced during recent decades, the water quality in the Keys is being degraded by human activities. In 1992, the Water Quality Protection Program identified inadequately treated wastewater and stormwater as primary sources of pollution to confined and nearshore waters of the Keys. Poorly treated wastewater and stormwater contain elevated concentrations of nutrients (e.g., nitrogen, phosphorus), that can cause algal blooms and degraded water quality. Discharges may also contain harmful bacteria and other pathogens that can pose a public health risk and can result in beach closings. Although the quality of offshore waters in the Florida Keys and Florida Bay can be influenced by external sources, such as the Loop Current and urban stormwater and runoff from the Florida mainland, evidence suggests that the quality of the Keys nearshore waters is strongly influenced by local anthropogenic sources.

On-site sewage treatment disposal systems and wastewater treatment plants

The groundwater and the nearshore waters in the Keys are closely connected. Wastewater effluent from on-site sewage treatment and disposal systems seeps into the surrounding porous limestone rock and can pollute the groundwater. Studies have shown that contaminated groundwater rapidly migrates to adjacent canals and basins, eventually discharging into and polluting nearshore waters. In 2000, the Monroe County Sanitary Wastewater Master Plan identified approximately 23,000 on-site sewage



There are many sources of pollution to nearshore waters in the Florida Keys.

treatment and disposal systems operating in the Florida Keys. The on-site systems consist mostly of septic tanks and at least 2800 illegal cesspools. There are also several hundred aerobic treatment units and approximately 250 permitted secondary treatment plants. Both aerobic treatment units and secondary treatment plants use shallow injection wells for effluent disposal. Septic tanks and cesspools provide little or no treatment because of the porous nature of the Keys limestone combined with the lack of soil and high groundwater. The permitted aerobic treatment units and the secondary treatment plants are designed to meet, at a minimum, secondary treatment and effluent disinfection, but they do little to remove nutrients.

W.L. Kruczynski - EPA

All long bridges in the Florida Keys have scuppers that discharge rainwater from roadways directly into surface waters.

Stormwater

Runoff from roads, residential areas, and businesses, including marinas and boat yards, can be a significant source of nutrient loading to surface waters. Untreated stormwater can also contain other harmful contaminants, such as bacteria, petroleum hydrocarbons, and toxic substances, such as lead and pesticides. Uncontrolled runoff can cause excessive turbidity in the water column that can be harmful to marine resources, such as seagrass beds and coral reefs. Because island settings have limited space, innovative methods to treat and dispose of stormwater are being investigated.

Discharges from vessels

Discharges from vessels account for a small percentage of the total nutrient loading to surface waters when compared with the nutrient input from land-based sources, such as septic tanks and stormwater runoff. However, sewage discharges from vessels can be a significant source of pollution in confined waters, such as anchorages and boat basins, where most vessels congregate. Petroleum discharges from vessels, such as fuel spills, can also cause significant harm to the Keys marine environment. Designation of all state waters in the Florida Keys National Marine Sanctuary as a no-discharge zone has resulted in a significant reduction of vessel discharges.

W.L. Kruczynski - EPA

Boats discharged their wastewater directly into surface waters before the advent of no-discharge zones.

Nutrients and pollutants from residential canals in the Florida Keys contaminate nearshore coastal waters

William L. Kruczynski, Gus Rios, and George Garrett

Canals were excavated to increase the area of waterfront development by dredging and filling mangrove shorelines. There are 481 canals in the Florida Keys, with a total length of 169 kilometers (111 miles). Differences in length, slope, depth, geometry, and underlying geology, as well as the population density, affect nutrient loading, flushing rates, and water quality within the canals and in nearshore coastal waters. All of the canal systems in the Keys have been inventoried and categorized by Monroe County. The inventory includes recommendations on how canal water quality and flushing rates can be improved.

Adapted from MACTEC (2003)

Port Largo Canal is a long, dead-end canal system with poor flushing. Canals were created by dredging and filling mangrove shorelines to create "fastland" for residential development.

Canals with poor water quality are listed in the Monroe County Sanitary Wastewater Master Plan. High nutrient concentrations are the result of sewage contamination, stormwater runoff, disposal of fish and yard wastes, and accumulation of floating dead seagrass and other organic debris.

In 1987, the Florida Department of Environmental Protection measured water quality at canal and nearshore sites in Marathon for 1 year to monitor leachate from poorly functioning on-site sewage systems. Coprostanol, a degradation product of cholesterol, is indicative of solids contamination (e.g., feces) and was found in high concentrations in the sediments of canals. Coprostanol levels were highest near the head of canals and decreased toward the canal mouth due to dilution from tidal flushing.

	Open Water	Eden Pines Canal
Total Nitrogen	0.1 – 10 µM	40.5 µM
Total Phosphorus	0.1 – 0.2 µM	1.04 µM
Chlorophyll *a*	0.2 – 0.5 µM	2.78 µM

Adapted from Florida Bay Watch

Nutrient and chlorophyll concentrations are much higher in many residential canals than in open water. Micromolar (µM) is a unit of concentration.

Dissolved oxygen is generally at or close to zero near the bottoms of most canal systems. Lack of oxygen is caused by poor mixing in the water column and breakdown of organic materials in the bottom of canals. Marine life in canals is restricted to organisms that live near the surface or can withstand low oxygen levels. Many residential canals violate State Water Quality Standards for minimum dissolved oxygen concentration (i.e., 4.0 milligrams per liter). All waters surrounding the Keys are designated as Outstanding Florida Waters, where any increase of pollutants above background levels is a violation of State Water Quality Standards. Thus, canal systems that discharge degraded water to coastal waters are sources of pollution.

W.L. Kruczynski - EPA

High nutrients result in algal blooms and low dissolved oxygen in canals.

Groundwater moves through the Florida Keys from the Gulf of Mexico to the Atlantic Ocean

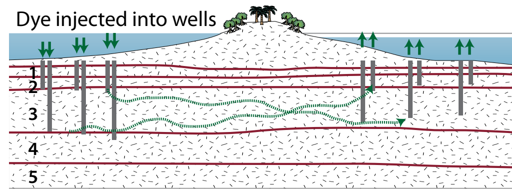
Eugene A. Shinn

The limestone under the Florida Keys is porous but not uniformly so. It was formed during the Pleistocene Epoch, a time when glaciers waxed and waned and sea level fluctuated many times. Coral reefs grew along the shallow Florida shelf each time the sea level was high. Each time the sea receded, the reefs and sands were laid bare and became cemented into limestone. A dense red-brown limestone crust called "calcrete" capped the rock each time the sea receded. The red-brown color is due to iron in dust that is periodically transported from Africa across the Atlantic Ocean on trade winds. Calcrete is a very impermeable layer, and there are five layers of calcrete in the upper 30.5 meters (100 feet) of limestone beneath the Keys. Because it is impermeable, it forces groundwater to flow sideways both between and across these layers. The layers of calcrete are numbered one to five and are referred to as Q Units for the Quaternary Period, the most recent period in geological history. The Q3 Unit is especially thick and extends throughout the region about 9.1 m (30 ft) below the surface.

To determine movement of water, a circular array of monitoring wells was drilled on both sides of Key Largo. Each well was constructed to allow sampling of water from above and below the impervious Q3 Unit. In the central well, one kind of tracer dye was injected above the Q3 and another dye below. By monitoring the peripheral wells, the direction and speed of movement of the dye was measured. Results showed that saline groundwater moved from the Gulf side of the Florida Keys toward the Atlantic Ocean underneath the entire width of Key Largo at a rate of about 1.8 m (6 ft) per day. Water above the Q3 moved more rapidly than water below that layer.

Water levels in Florida Bay (Gulf side) fluctuate mostly because of wind; there are very small lunar tides in Florida Bay. Lunar tide fluctuation on the Atlantic side of the Keys is about 0.9 m (3 ft) and occurs twice a day (diurnal). Measurements show that the average water level on the Bay side is several inches higher than on the Atlantic side. This creates a hydraulic head, and water runs downhill. When the Atlantic tide is low, there can be 0.9 m (3 ft) of difference in water level, and the rate of water moving toward the Atlantic is fast. When the Atlantic tide is high, the direction of flow reverses for awhile. This back-and-forth sloshing causes tidal pumping. During low tide, not only does the water move faster from the bay toward the ocean, but also the hydraulic head pushes groundwater about 0.3 m (1 ft) above sea level. At those times, water boils out of the rock where there are cracks and crevices. Even though the groundwater sloshes back and forth like water in a bathtub, the net flow is toward the Atlantic.

Any contaminants entering the groundwater of the islands from sewage or stormwater injection wells, septic tanks, or lawn fertilization become mixed with the flow and move toward the Atlantic. When the Atlantic tide is low, the hydraulic head diffuses upward under pressure. Studies using bacterial and viral tracers have found that the groundwater from the Keys may reach the surface water near the bank reef.

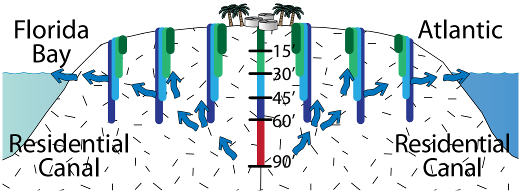


Bay to ocean groundwater flow model representing net direction of groundwater movement during normal conditions based on dye studies. The left margin of the diagram shows the relative depths of Q1 – Q5 Unit layers.

Nitrogen and phosphorus from wastewater disposed into injection wells enters surface waters

Kevin Dillon

Conventional, secondary wastewater treatment plants produce an effluent that is rich in nitrogen (nitrate) and phosphorus (phosphate) nutrients. In the Florida Keys, the effluent is injected into Class V (shallow) injection wells. Class V wells are drilled into the limestone to a depth of 27 meters (90 feet) and are cased with an impermeable lining to 18 m (60 ft), so the zone of discharge is between 18 – 27 m (60 – 90 ft) below the surface.

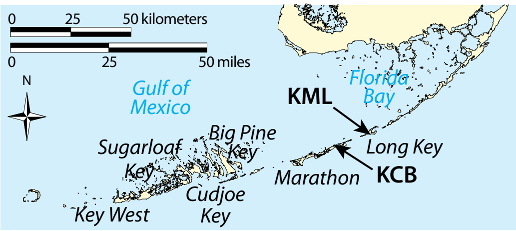


Cross section of an array of sampling wells surrounding a Class V injection well to determine rate and direction of wastewater plume and concentration of nutrients as the plume moves through limestone.

The groundwater beneath most of the Keys is saline, whereas the wastewater effluent is relatively fresh. After injection into a well, the less dense, buoyant wastewater plume rises toward the surface. Research investigating the movement of the wastewater plumes and the fate of nutrients from Class V injection wells was conducted at two sites in the Keys. The Keys Marine Laboratory has a low volume 2650 liters (700 gallons) per day disposal well on Long Key. Key Colony Beach has a relatively high disposal volume of 946,000 L (250,000 gal) per day. Monitoring wells were installed around each injection well and were drilled to 4.6, 9.1, 13.7, and 18 m (15, 30, 45, and 60 ft). Samples were taken from monitoring wells to assess nutrient concentrations of subterranean wastewater and movement of plumes using tracers (dyes and other chemicals).

Results demonstrated that wastewater is rapidly transported upward toward the surface and laterally (up to 6.4 m [21 ft] per day), which delivers tracers placed into injection wells to nearby surface waters after several days to weeks (10 and 60 days at Keys Marine Laboratory and Key Colony Beach, respectively). As the wastewater flows through cracks and fissures in the limestone, denitrifying bacteria remove 30% – 90% of the nitrate from the underground plume and convert it to harmless nitrogen gas.

Phosphate in wastewater is initially removed from solution by chemical adsorption onto the limestone; however, this sequestration is short lived. The limestone acts as a phosphate buffer, temporarily adsorbing 50% – 100% of the phosphate from solution until an equilibrium concentration of 0.8 parts per million is achieved. Once that concentration is established, it persists even when phosphate-free water is added to the system, due to the release of bound phosphate from the saturated limestone. So with time, the limestone can get saturated with phosphate and no longer removes it from the wastewater. Although more research is needed to fully understand this process, it appears that phosphate equilibrium plumes form around injection wells and slowly expand as more phosphate is added to the system until the plumes eventually reach surface waters.



Locations of research sites: Keys Marine Laboratory (KML) on Long Key and Key Colony Beach (KCB).

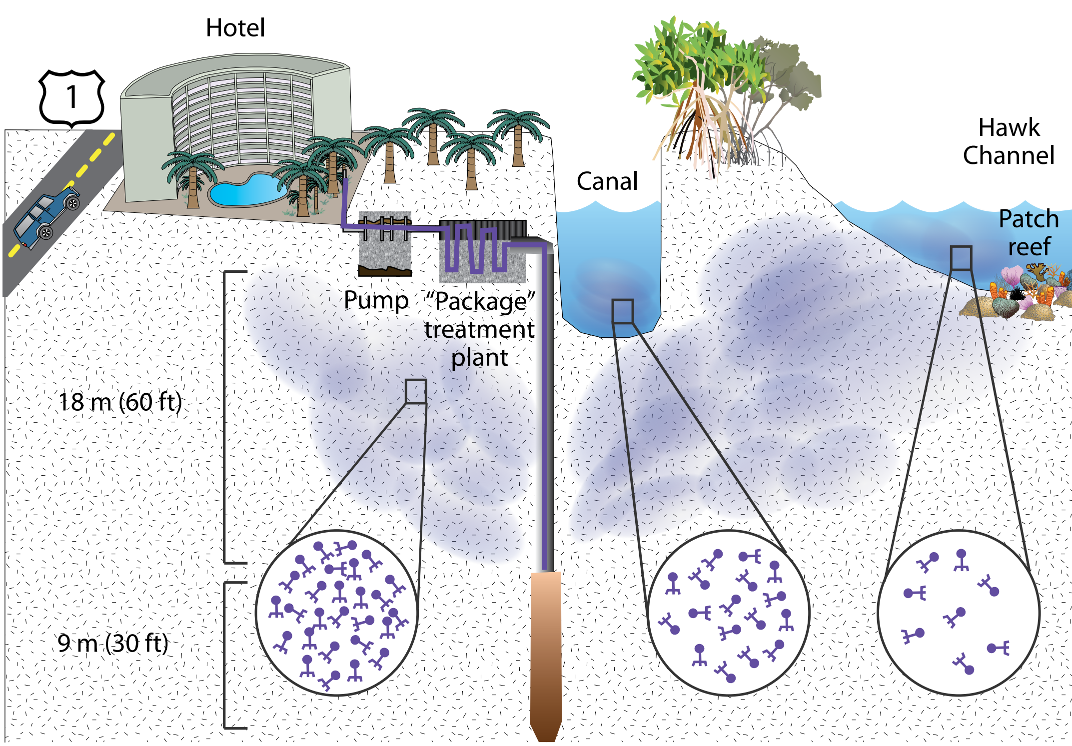
Water Quality

Wastewater disposed into shallow injection wells can be tracked using viral tracers

John H. Paul

Class V injection wells comprise a wastewater disposal system that is commonly used by secondary treatment package plants in the Florida Keys. To determine whether such wells could result in contamination of surface waters in the Keys, viral tracer studies were performed in two Class V wells using a harmless bacteriophage. Bacteriophages are viruses that infect bacteria; they cannot infect humans. Bacteriophages not found in the Florida Keys will not multiply in the environment because their host is not found there; therefore, they make useful tools as tracers of wastewater movement.

A bacteriophage was grown to a high concentration in the laboratory and used to "seed" the injection wells over a 4-hour period. At the Saddlebunch Keys site, the rate of movement of the viral tracer away from the injection site ranged from 1.2 – 141 meters (4 – 463 feet) per hour; at Long Key the movement ranged from 0.35 – 22.5 m (1.2 – 74 ft) per hour. This means that sewage injected into the well moved away from the point of injection quickly. Thus, nutrients, microbes, or other contaminants in the sewage effluent can quickly contaminate the surface waters.



Generalized diagram showing package treatment plant, injection well, and adjacent canal and open waters (Hawk Channel). Bacteriophage tracer plume (purple cloud) spreads from point of discharge. Highest concentrations of tracer viruses were found near discharge zone, but tracer viruses were also found in the adjacent canal and surface waters (Hawk Channel). These studies demonstrate that Class V injection wells can cause contamination of surface waters in this environment because of the porous nature of the limestone substrate.

Pathogenic human viruses are present in residential canals

Dale W. Griffin

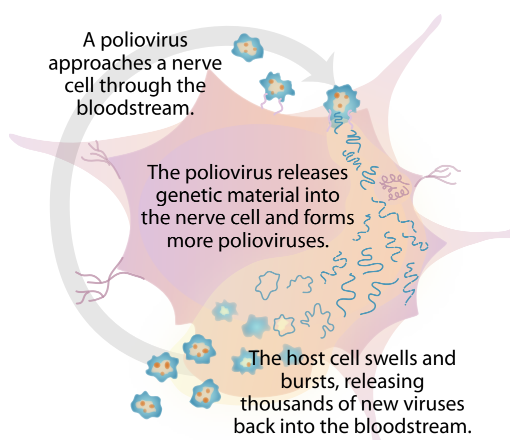
In the late 1990s, there were approximately 23,000 on-site sewage treatment and disposal systems, 2800 illegal cesspools, and 670 shallow injection wells 18 – 27 meters (60 – 90 feet) deep in the Keys. Small package sewage treatment plants disinfect wastewater to kill pathogenic and nonpathogenic microorganisms and dispose of the treated wastewater into shallow injection wells. However, they are a source of household chemicals, pharmaceuticals, and nutrients. Septic systems and cesspools not only are a source of nutrient and pharmaceutical pollution but can also be a source of pathogenic and nonpathogenic microorganisms to nearby bodies of water because those systems do not disinfect wastewater, .

Studies have been conducted using bacteriophages (viruses that infect bacteria) to trace the fate of wastewater from septic systems and shallow injection wells. Several studies performed to trace the fate of wastewater disposed into shallow injection wells in the Middle and Lower Keys demonstrated a rapid transport of wastewater to canals and nearshore surface waters. In one experiment that flushed bacteriophages into a septic tank, the organisms were detected in a nearby Key Largo canal 11 hours after they were flushed. In another experiment in Marathon, bacteriophages were found in a canal connected to Boot Key Harbor 3 hours after being flushed into a septic tank.

Are discharges from septic systems and cesspools a risk to ecosystem and human health?

Fecal microbes have the potential to displace native microbes and to disrupt essential ecosystem cycles. They have also been shown to cause a disease in marine organisms. *Serratia marcescens*, a bacterium found in the human intestinal tract and other places, such as soil, causes white-pox disease in elkhorn coral (*Acropora palmata*). Many viruses that infect people have a fecal-oral pathway of infection and typically have "shed rates" of 1 million viruses per gram of feces. Pathogenic viruses can infect people at very low doses (in some cases fewer than five viruses) and so it does not take much fecal contamination for waters to be a concern for human recreational uses.

To investigate the risk of fecal microbes to human health, 19 sites in the Florida Keys were screened for the presence of indicator bacteria (i.e., total coliforms, fecal coliforms, *Escherichia coli*, *Clostridium perfringens*, and enterococci), coliphage, and four groups of pathogenic human viruses (i.e., enteroviruses, Hepatitis A viruses, Norwalk viruses, and Norwalk-like



Adapted from Smithsonian National Museum of American History

The life cycle of a poliovirus. Enteroviruses include echoviruses, coxsackie viruses, and poliovirus. These viruses are actively shed by up to 30% of the population. In most cases, they cause asymptomatic infections (i.e., no sign of illness), but on occasion, they can cause a variety of illnesses, including flu-like symptoms, gastroenteritis, meningitis, and myocarditis, that can be lethal. Although the polio vaccine program has been very successful at preventing the disease, it is not unusual to detect the poliovirus (vaccine strain) in Florida waters affected by human feces.

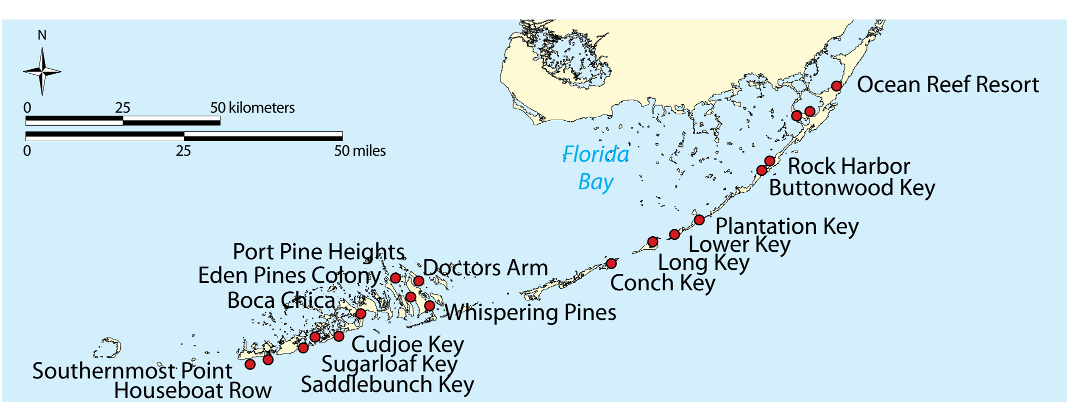
viruses). In this first study, no distinction was made between living or dead human viruses. Of the 19 sites, all but one were positive for at least one of the groups of viruses, while at the same time the bacteria data indicated good to fair water quality. The one exception was the sample taken near the Southernmost Point in Key West where the bacteria counts were also high because the city sewer system had been leaking at this site. (Key West has since upgraded its sewage collection system and now discharges into a deep well instead of an ocean outfall.)

The sites that typically had the highest counts of human viruses were canals with homes using septic systems that were part of an extensive canal network that offered no means of effective flushing (e.g., Eden Pines Canal system on Big Pine Key). The sites with the lowest counts of microbial indicators had well flushed or flow through canal systems or were connected to a central collection and treatment system.

Follow-up studies detected live and infectious enteroviruses in canals during periods when surface waters were cool. This finding emphasized the conclusion that the currently used indicator bacteria (i.e., fecal coliform and enterococci) do not accurately assess human health risk. In most cases in tropical environments, indicator bacteria are poor proxies of water quality, and pathogenic human fecal-oral microorganisms can be present when bacteria data indicate that the water is safe for recreational use. These and other studies have unequivocally demonstrated that septic tanks or cesspools, as well as leaking central collection systems, installed in porous limestone substrate in proximity to marine surface waters pose a risk to human and ecosystem health. Regulatory agencies should thoroughly evaluate hydrogeologic conditions before permitting septic tank installations in the Florida coastal environment. Conversion to central collection and sewage treatment systems will provide an increased level of protection to public health and to the unique and sensitive environments that are present in the Florida Keys.

W.L. Kruczynski - EPA

A film of scum on the surface of the water at the dead end of a multichannel canal network on Big Pine Key. Canals that are bordered by homes using septic systems should be viewed as an extension of the septic tank network, and recreational use of the canal waters should be avoided.



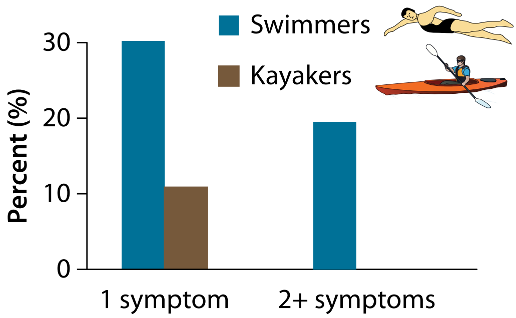
Sample site locations for bacteria and virus counts in the Florida Keys. The study showed that human viruses could be present in significant numbers when fecal bacteria counts were below State of Florida standards.

In-ground disposal of human sewage can contaminate nearshore waters and reefs with bacteria and viruses

Erin K. Lipp, Dale W. Griffin, and J. Carrie Futch

Historically, much of the sewage in the Florida Keys was disposed into on-site septic tank systems or, in some cases, cesspools. Cesspools are holes in the ground that provide no treatment of sewage. When septic tank systems function properly, the drainfield allows slow filtration and natural "treatment" of wastewater through an area of dry soil. Treatment of wastewater breaks down when the drainfield occurs in wet or saturated soils, which exist in areas with a high groundwater table, such as low-lying and coastal areas. Also, when the density of septic systems is high, the wastewater saturates the ground, and there may be insufficient area for proper filtration. Unfortunately, both of these problems arise, sometimes simultaneously, in the Florida Keys, leaving the groundwater and adjacent surface waters, including residential canals, vulnerable to contamination with bacteria and viruses found in human feces. The presence of these microbes has been used as a tracer to show that nutrients or other contaminants in human sewage are reaching coastal waters. Their presence can pose a threat to public health because many of these microbes cause a range of diseases, especially diarrhea and vomiting, when accidentally ingested while swimming.

Studies beginning in the mid-1990s show that viruses in particular can move quickly (within 11 hours in some cases) from a septic system to adjacent canal and nearshore waters. Additionally, 95% of the canals tested in 1998 contained one or more types of viruses that can infect humans. In 1999, as many as 30% of competitive swimmers in a 19 kilometer (12 mile)-race around Key West reported one or more symptoms of waterborne diseases (i.e., eye, ear, and nose problems; gastrointestinal and respiratory issues;



During the Annual Swim Around Key West in June 1999, 30% of swimmers (blue bars) reported at least one symptom of a waterborne disease, and 20% reported two or more symptoms. Only 10% of kayakers on the same route (control group, open bar) reported one symptom, and none reported multiple symptoms.

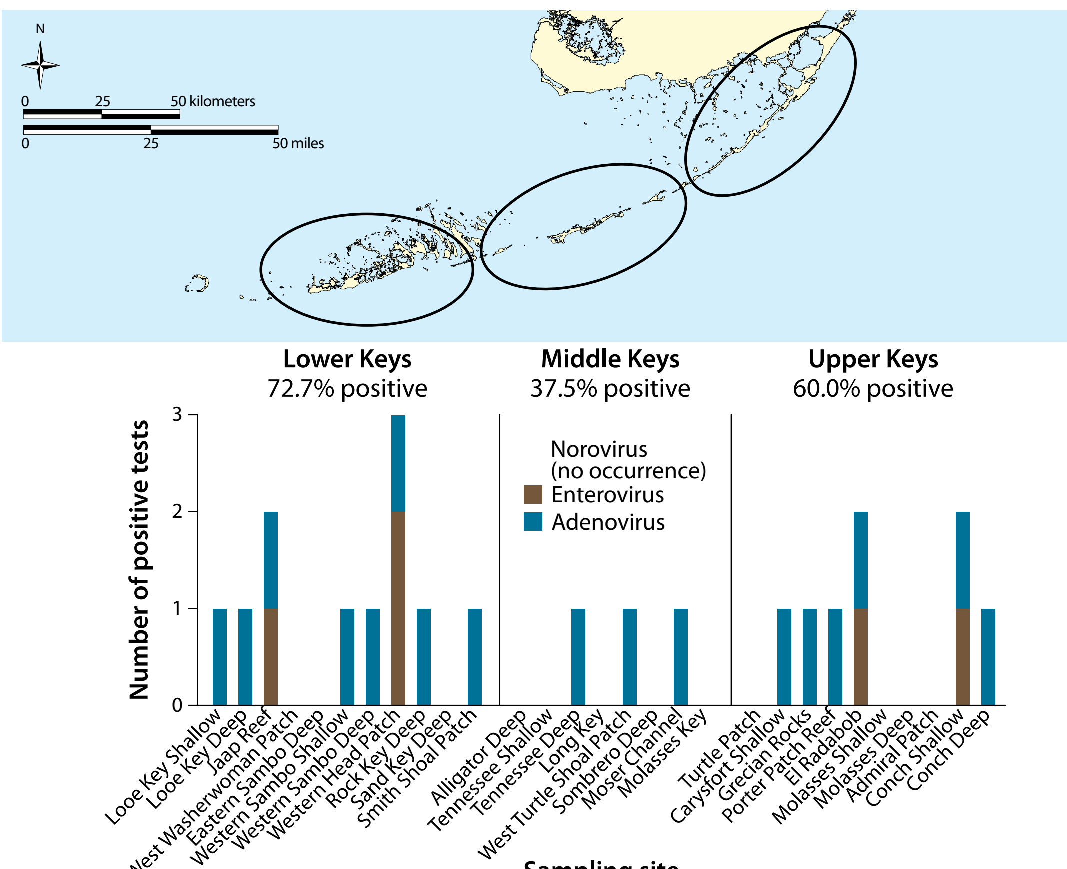
E. Lipp - UGA

Beaches in the Florida Keys are occasionally closed due to high levels of fecal indicator bacteria (Key West Citizen, July 17, 1999). Closed beaches can affect tourism and the economy.

skin rashes; and diarrhea) likely associated with swimming in contaminated water. After completion of the 1999 race, beaches in Key West were closed due to high bacterial counts.

Contamination is not restricted to nearshore waters. The genetic material of human viruses has been detected from groundwater wells and the mucus layer of corals as far as 10 km (6.2 mi) offshore. The distribution of these viruses in coral mucus corresponds with the distribution of large population centers in the Florida Keys. Highest levels were found in corals off Key West and Key Largo, and lower frequency of viral contamination occurred in corals found off the Middle Keys.

Monroe County completed its Sanitary Wastewater Master Plan in 2000, and work has begun to improve wastewater collection and treatment. Increased levels of treatment should improve water quality by reducing the levels of nutrients and human pathogens discharged into waters surrounding the Florida Keys. Key West upgraded its treatment to Advanced Wastewater Treatment, eliminated its open water discharge in 2002, and has re-sewered the city to separate stormwater from sewage. Monroe County and other municipalities are in varying stages of improving wastewater treatment to satisfy requirements of State of Florida Law 99-395.



Mucus samples from corals were collected from reefs throughout the Florida Keys and analyzed for the presence of three types of human viruses found in human sewage (noroviruses, adenoviruses, and enteroviruses). Results of the analyses are presented as number of times a reef was positive for each of the viruses. Reefs in the Upper Keys (including Key Largo with a population of approximately 26,000 people) and Lower Keys (including Key West with a population of approximately 39,000 people) had the highest percentage of reefs positive for human viruses, whereas the frequency of virus detection was considerably lower in the Middle Keys (with a human population of approximately 11,000).

Navigational inlets are conduits for land-based sources of pollution

J. Carrie Futch, Dale W. Griffin, Ken Banks, and Erin K. Lipp

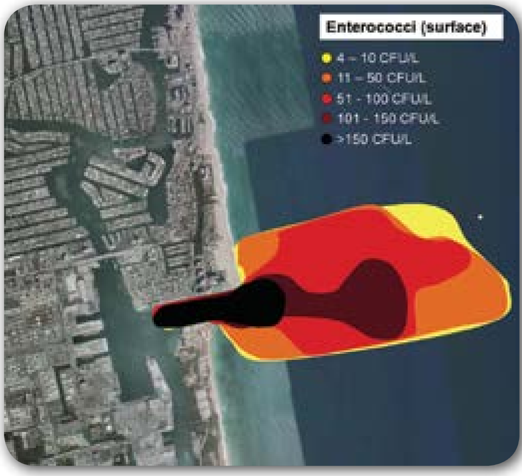
Large navigational inlets in southeast Florida can act as conduits of wastewater and stormwater pollutants from developed areas to nearshore marine waters. Pollutant constituents can affect human recreational use and ecosystem health. These discharges, in combination with regulated releases of inland waters, such as freshwater from Lake Okeechobee, can result in contamination of nearby ocean waters.

In Broward County, Port Everglades is a large commercial port that receives waters from the Middle River, New River, and the Dania Cutoff Canal as well as influxes from urban stormwater and agricultural runoff via the Intracoastal Waterway. Untreated sewage from spills or leaks from improperly functioning septic tanks can enter these waters. Contaminants that reach the Intracoastal Waterway are eventually subject to tidal mixing with ocean waters through Port Everglades Inlet.

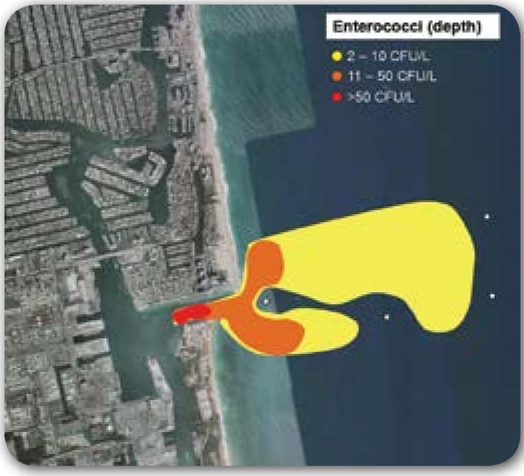
Research conducted offshore from Port Everglades Inlet indicates that sewage and other wastewater contaminants are affecting ocean waters, coral reefs, and nearby beaches. Samples collected on an outgoing tide at the Port Everglades Inlet contained multiple types of noroviruses in addition to other microbes found in human sewage. Elevated levels of pharmaceuticals typically present in sewage were also found. Noroviruses are one of the most common causes of diarrhea in adults, and infamously known as the "cruise ship virus."

NOAA image enhanced by R. Dodge - NSU

Aerial photograph of outgoing tide at Port Everglades Inlet (circa 1981). The inlet may act as a conduit for pollution to the marine environment, introducing bacterial and viral contamination. Image has been enhanced to increase visibility of the Intracoastal Waterway and water exiting the inlet.



Google Earth; source data from D.W. Griffin



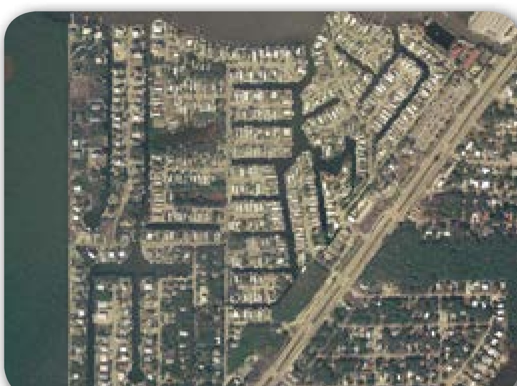
Google Earth; source data from D.W. Griffin

Colorized plots show the concentration of sewage-associated bacteria (enterococci) as it exits the Port Everglades Inlet on the surface (left) and on the bottom (right) during an outgoing tide. Black and red are the highest concentrations (CFU/L =colony forming units per liter of water); yellow is the lowest concentration.

Improving wastewater and stormwater treatment reduces nutrient loading to canals and nearshore waters

Scott McClelland and Stephen R. Lienhart

The Florida Keys is a chain of islands approximately 350 kilometers (220 miles) long, extending from the end of the Florida peninsula and curving southwest toward the Dry Tortugas. Consisting of 822 islands, of which about 30 are inhabited, the Florida Keys are traversed by U.S. Highway 1 that includes 30 km (19 mi) of bridges. Key West represents about 31% (24,630 people) of the population of the Florida Keys, which is about 78,990 people according to the Bureau of Economic and Business Research for April 1, 2007.

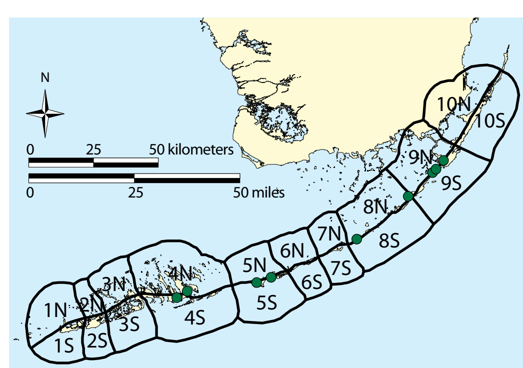


FDEP

Aerial view (2004) of densely populated canal developments in Key Largo. Historically, poor wastewater and stormwater treatment as well as poor circulation and flushing resulted in degraded water quality in canals.

Residential canals were excavated in the Florida Keys during the development of the inhabited islands to provide waterfront access for residents. Canal systems were designed to maximize development with little regard to water quality. Currently, water quality in canals is poor due to inadequate wastewater and stormwater treatment, as well as limited circulation and tidal flushing. In addition, weed wrack (i.e., detached seagrass blades) collects in some canals, decomposes, and forms an organic ooze in the canal bottom that consumes dissolved oxygen and releases nutrients.

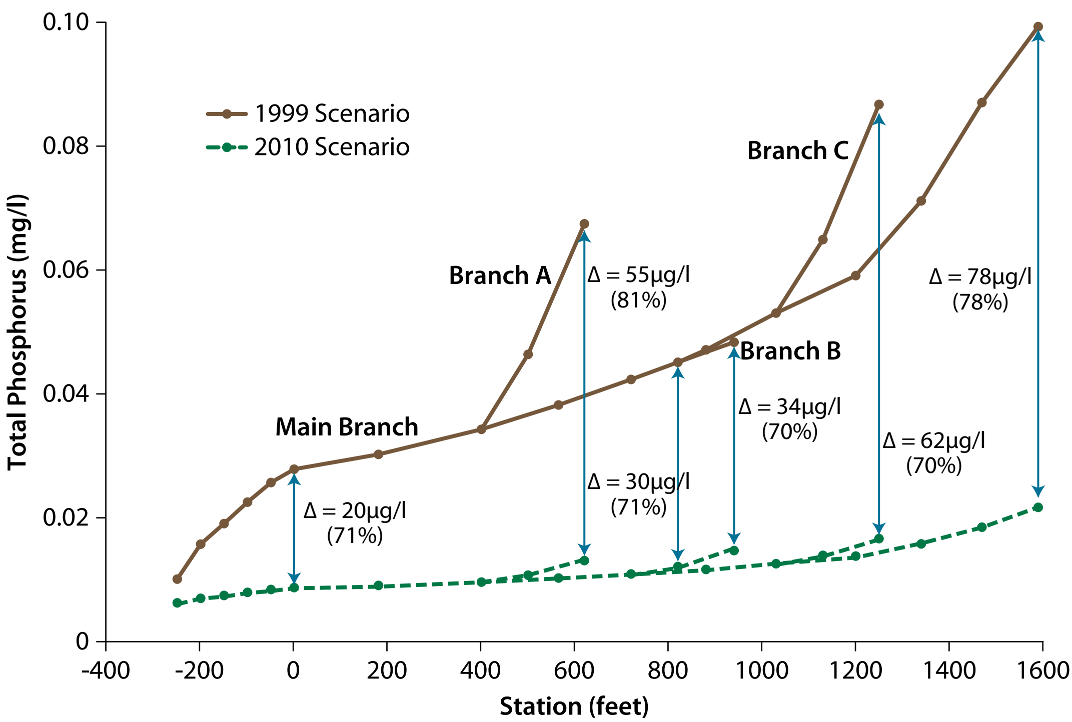
The Florida Keys Reasonable Assurance document considered the potential impacts of anthropogenic nutrient loading of the nearshore waters of the Florida Keys, including the many canals. The nearshore waters of the Keys were divided into 20 modeling areas from the shoreline to about 12.1 km (7.5 mi) offshore. Also, 10 representative canals were modeled, and nutrients from the land (i.e., wastewater, stormwater, urban and natural runoff) were loaded into the shoreline boundary of the models. The models advectively distributed the loads through mixing and tidal dynamics until steady state was reached. These models were used to test the potential nutrient concentration that may result from the significant wastewater and stormwater improvements being made in the Keys. The modeling showed that at 500 meters (1600 feet) from the shoreline, the improved anthropogenic nutrient loading would result in total nitrogen and total phosphorus concentrations less than 10 µg/l and 2 µg/l above natural background concentrations, respectively.



Location of 20 nearshore areas and 10 residential canals (green dots) that were modeled to show that improved anthropogenic nutrient loading would reduce total nitrogen and total phosphorus to near background concentrations.

Natural background concentrations were simulated by eliminating anthropogenic inputs (i.e., point sources) and changing urban land uses into natural lands. Furthermore, the nearshore nutrient concentrations are predicted to return to ambient values similar to or less than those measured during the time when the Keys were designated Outstanding Florida Waters.

Modeling of the 10 representative canals provided similar results. Canals were modeled to assess changes in total phosphorus for the 1999 baseline condition (believed to be the worst case) and the 2020 improved condition when the majority of the nutrient reduction activities are expected to be completed. Results for Canal 50 (in Key Largo) show that total phosphorus in 1999 was about 0.01 mg/l at the canal mouth and increased 10 times to 0.10 mg/l at the end of the main channel. Canal 50 has three dead-end branches: A, B, and C. The model predicts that in 2020, there would be a 71% reduction in total phosphorus in the main branch and 70% – 81% reductions in the canal branches. These results are due to decreased wastewater and septic tank inputs into the canal and improved nearshore nutrient conditions, primarily the result of a reduction of anthropogenic influences. Ancillary benefits may also be achieved with reduced septic loads, including reduced enteric bacteria (i.e., fecal coliform and enterococci) and viruses. Nutrient reduction activities will return the quality of nearshore waters to historical levels. However, even with reduced nutrient loads to canals, poor tidal flushing, limited circulation, and the presence of weed wrack will still limit the water quality in the canals.



Results of modeling total phosphorus concentration in a residential canal (Canal 50) in the Florida Keys before (brown) and after (green) improvements to sewage treatments. Total phosphorus concentration is shown on the y-axis (mg/l). The figure shows a canal with a main branch and three side branches (Branch A, B, and C). The solid red line represents the 1999 time period, which assumes the worst case conditions (i.e., high phosphorus concentrations). The dotted green line shows modeled concentrations after sewage and stormwater improvements have been implemented. Total phosphorus concentration would decrease by 71% at the mouth of the canal and midway on the main branch, and 81%, 70%, and 78% in Branches A, B, and C, respectively.

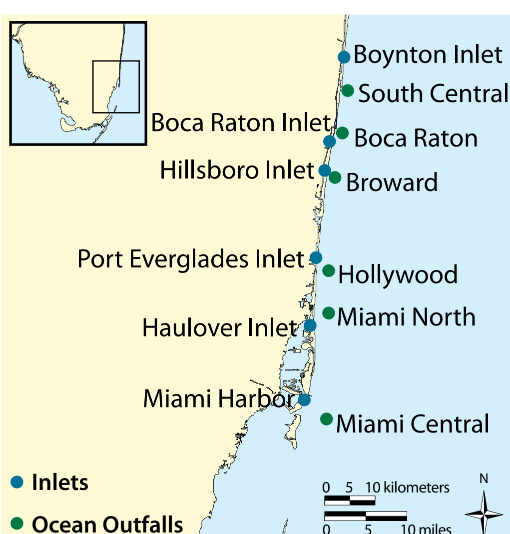
Water Quality

The Florida Area Coastal Environment Program supports science-based water quality management

Thomas Carsey and Jack Stamates

The Florida Area Coastal Environment (FACE) Program is an ongoing research effort led by the National Oceanic and Atmospheric Administration (NOAA) Atlantic Oceanographic and Meteorological Laboratory since 2004. The FACE Program highlights the need to comprehensively assess the coastal zone to help understand the impacts of land-based sources of pollution on southeast Florida coral reef habitats and to formulate science-based management. The broad objectives of the program include the following:

- Quantifying the sources of nutrients and microbial contaminants;
- Quantifying the relative contributions of those sources to the nutrient budget and microbiological loads of the region; and
- Determining the likely exposure of coral reef resources to nutrient and microbiologic sources.



Study sites of the FACE Program include inlets and ocean outfalls from sewage treatment plants from Miami (Miami-Dade County) to Boynton Inlet (Palm Beach County).

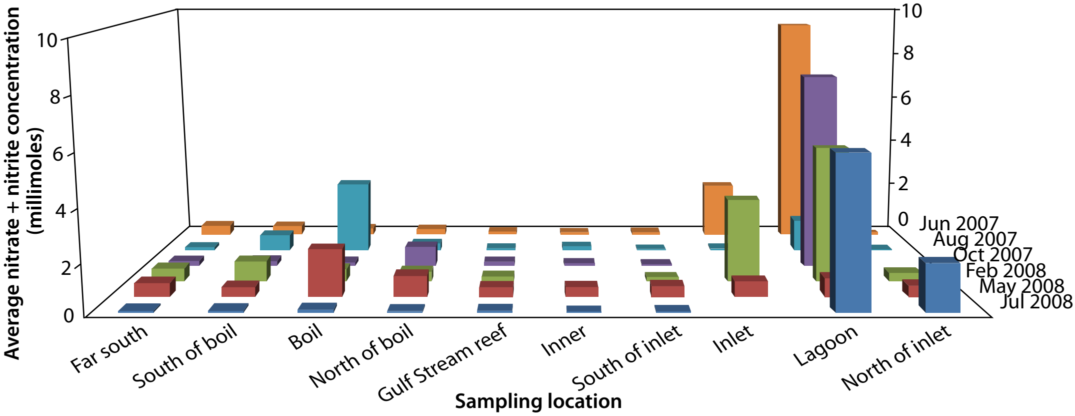
This extensive field program has performed surveys of sewage outfalls at all six existing wastewater plants in the study area (Miami Central, Miami South, Hollywood, Broward, Boca Raton, and South Central) and at several inlets and their respective receiving waters. Ultimately, FACE will undertake detailed physical, chemical, and biological studies at each inlet and outfall, including recording ocean currents, nutrient concentrations and source tracking, microbiology, and stable isotope analyses. Examples of information from some completed studies are given here.

Tracer studies

A study was conducted at the Hollywood Wastewater Treatment Plant outfall in June 2004 using sulfur hexafluoride to trace the direction of the outfall plume (i.e., boil). Sulfur hexafluoride is a humanmade compound. The plume was traced flowing north, near the coast, for 66 kilometers (41 miles). A second tracer study was performed near the outfall of the South Central Regional Wastewater Treatment Plant and in nearby Boynton Inlet in 2007. Results suggested a rapid dilution of the outfall effluent by the surroundings waters. Waters exiting Boynton Inlet were traced over 34 km (21 mi) north of the inlet.

Currents

Measurements of currents help to elucidate sources of water that can affect important coral communities. Ocean current data have been measured at several locations off Palm Beach County for extended periods of time. For example, instrumentation at the north end of Gulf Stream Reef from April 2006 – September 2007 recorded a northerly current flow 86% of the time.



Averaged concentrations of nitrate and nitrite from six bimonthly cruises from south of the South Central ocean outfall (i.e., boil) to north of Boynton Inlet. Horizontal axis names refer to sampling regions. Seasonal variation and variation by site are shown in this three-dimensional graph.

Nutrients

Nutrients (e.g., nitrite, nitrate, orthophosphate, silicate, ammonia) were measured during intensive studies at the Boynton Inlet and at all six wastewater treatment plant ocean outfalls. These results help to evaluate the relative concentration as well as the dilution of these nutrients in the receiving waters. Elevated nutrients were found near the outfall boils and at Boynton Inlet.

Inlet studies

Detailed flow, chemical, and microbiological sampling measurements were made at the Boynton Inlet during two 48-hour-long studies. These studies noted considerable, but highly variable nutrient flux. Additional inlet studies are planned.

Microbiology

A variety of microbial contaminants were measured at sewage outfalls and at several inlets and adjoining waters. High bacterial counts (*Methanobrevibacter smithii*), viral counts (*Norovirus*), and intestinal parasitic protozoans (*Cryptosporidum* and *Giardia*) were detected at sewage outfalls and during outgoing tides from inlets. A comparison of results from the six outfalls shows the highest concentrations of microbial contaminants at the Miami-North boil.

Location	*M. smithii* (GE*/100mL)	*Norovirus* (GE*/100mL)	*Cryptosporidium* oocysts	*Giardia* cysts/100L
South Central boil	700	no detection	no detection	no detection
Hollywood boil	3.0×10^5	235	55	67
Boca Raton boil	2.7×10^4	2.3	<1	<1
Broward boil	3.7×10^5	6.3	8	2
Miami-North boil	1.3×10^5	347	236	246
Miami-Central boil	3.4×10^5	11	8	120
Deep-water control	no detection	no detection		

*GE = Genome Equivalent is a measure of the abundance of microbes.

Abundances of microbes, including intestinal bacteria (*Methanobrevibacter smithii*), human viral pathogens (*Norovirus*), and intestinal parasitic protozoans (*Cryptosporidium* and *Giardia*) from surface water at wastewater ocean outfalls (i.e., boils) and a deep-water control site, February 2008.

Water Quality

Pharmaceuticals are present in wastewater discharges

Piero R. Gardinali

Coastal habitats are among the most productive and diverse components of the marine ecosystem but are also the most vulnerable to pollution. South Florida contains vital fresh, estuarine, and saltwater habitats that are linked by complex hydrological and biological connections. Because southeast Florida coastal habitats are adjacent to large population centers, they are adversely affected by physical abuse and through the discharge of pollutants. One type of pollutant that has only recently received attention is the discharge of personal care products and pharmaceuticals (i.e., microconstituents) into surface waters. These microconstituents include insect repellents, sunscreens, fragrances, plasticizers, human and veterinary pharmaceuticals, anti-inflammatory drugs, antibiotics, birth control hormones, and other drugs.

M. Averette

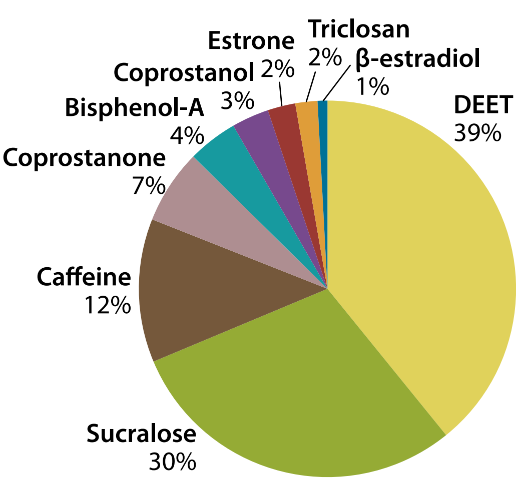
The Miami River is an urban river that receives point and nonpoint pollution from many sources.

Some common microconstituent pollutants

- **β-estradiol**: A main component of human estrogen hormone and an endocrine-disrupting hormone.
- **Bisphenol-A**: A chemical found in food containers and reusable plastic bottles and an endocrine-disrupting compound.
- **Caffeine**: A stimulant found in coffee, sodas, sports drinks, and drugs.
- **Coprostanol/coprostanone**: Metabolites of cholesterol used as a tracer of human fecal contamination in the environment.
- **DEET**: A chemical used in insect repellents.
- **Estrone**: A human estrogen hormone that is an endocrine-disrupting hormone in the environment.
- **Sucralose**: An artificial sweetener that is resistant to conventional wastewater practices.
- **Triclosan**: An antibacterial chemical found in soaps, detergents, and some plastics.

Modern wastewater treatment facilities can remove nutrients prior to discharges to surface waters or groundwater. However, unregulated organic chemicals commonly used as personal care products have been found to survive the treatment process and have been increasingly detected in wastewater discharges from central treatment facilities, on-site systems, and surface coastal waters worldwide. The occurrence, fate, and transport of microconstituent pollutants are being studied to understand their sources and dissipation in coastal environments. However, their environmental toxicology, including the risks associated with their presence, is less well known.

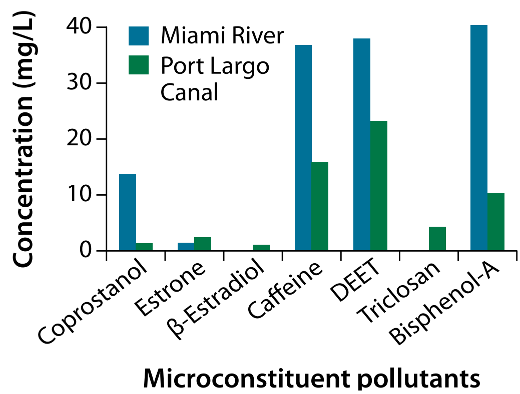
Communities are turning to water reuse, recharge, and reclamation because clean drinking water is becoming scarce. A major challenge in the use of these solutions for water conservation is the presence of microconstituents that survive traditional wastewater treatment methods. A case in point is estrone, an endocrine-disrupting hormone that can affect development and reproduction of fishes in concentrations as low as a few parts per trillion. Estrone has been found to be ubiquitous in surface waters and reclaimed wastewater. It was the most common microconstituent in Little Venice canals (Florida Keys) where most of the homes were on cesspools or poorly functional septic tanks before improved wastewater treatment became available. Other endocrine-disruptive chemicals found in south Florida waters include an estrogen derivative (β-estradiol) and a plasticizer (Bisphenol-A).



Composite of the chemical ecology of surface waters of the Miami River, Port Largo Canal (Key Largo), Little Venice canals (Marathon), and Looe Key showing all the microconstituents found and their relative percentage.

The artificial sweetener sucralose (Splenda®) is chlorinated table sugar that has a long shelf life and is very stable at high temperatures. These qualities, exceptional for food manufacturing, make it resistant to conventional wastewater treatment practices. Sucralose is very common in wastewater and in both nearshore and offshore surface waters in the Florida Keys. DEET, an active ingredient in insect repellents, and caffeine from coffee, tea, and soft drinks are also common in south Florida waters.

Microconstituent pollutants are so varied in their chemical composition, volume, and stability that detailed studies are needed on local and regional scales to assess the chemical ecology of receiving waters. For example, the Miami River has a different chemical "fingerprint" of microconstituents than Port Largo Canal (Key Largo).



The chemical "fingerprint" of microconstituents in the Miami River (blue) and Port Largo Canal (green) are very different.

Coprostanol is related to cholesterol and is commonly used as an indicator of sewage pollution. Coprostanol is found in higher concentrations in the Miami River than in Port Largo Canal, whereas triclosan, a compound commonly used in antibacterial soaps and detergents, was more prevalent in Port Largo Canal and absent from the Miami River.

At present, the best management practices and the most effective strategies to prevent chronic releases of microconstituents include development of effective wastewater treatment methods and consumer-based education programs stressing proper household disposal. Monitoring programs should include a suite of microconstituents so that risks associated with the fate and transport to marine ecosystems can be assessed and information can be used to develop science-based management actions.

Boot Key Harbor shows successful water quality improvements

William L. Kruczynski and Richard Tanner

On June 19, 2002, all State of Florida waters within the Florida Keys National Marine Sanctuary became a no-discharge zone for sewage from all vessels. The designation was made by the United States Environmental Protection Agency at the request of Monroe County and the Governor of Florida.

> **No-discharge zone**
>
> A no-discharge zone is a geographic area where discharge of sewage (i.e., blackwater), whether treated or not, is prohibited from all vessels. It is illegal to discharge sewage from boats into surface waters in a no-discharge zone. Discharge of gray water (galley, showers, washdown water) is not illegal in a no-discharge zone.

Why was this action taken?

The biological resources of the Florida Keys National Marine Sanctuary depend on clear, low nutrient waters. It is estimated that vessels account for about 3% – 5% of total nutrients discharged to Sanctuary waters. However, vessel discharge constitutes a significant source of water pollution in harbors, marinas, and other areas with poor circulation. Treatment provided by marine sanitation devices on vessels disinfect the waste but

P. J. Smith

Boats moored at some of the 226 mooring balls in Boot Key Harbor, Marathon, Florida.

do not remove nutrients. Excess nutrients result in water quality degradation. Prior to this designation, houseboats were required to have sewage pumped out, whereas transient vessels could discharge wastewater directly into surface waters. In a no-discharge zone, all vessels are required to store their sewage in a holding tank and have that tank pumped out at an approved facility. A list of available pump-out facilities in the Florida Keys is given at http://fl-monroecounty.civicplus.com/DocumentView.aspx?Did=313

finalized, 226 mooring balls were installed, pump-out was facilitated by available onshore facilities and mobile pump-out boats, and a dock master was hired to oversee activities in the harbor.

In 2004 – 2005, the first year of operation of the completed facilities, 6568 vessels were pumped out, removing approximately 375,000 liters (99,000 gallons) of sewage that would have been discharged into the harbor. In 2007 – 2008, approximately 591,000 L (156,000 gal) of wastewater was properly disposed

W. L. Kruczynski - EPA

Pump-out facilities removed 99,000 gallons of vessel sewage during the first year of operation in Boot Key Harbor. Before the no-discharge zone designation, sewage would have been discharged directly to surface waters.

Boot Key Harbor

In 1990, the Florida Department of Environmental Regulation conducted an intensive 1-year study in Boot Key Harbor and found low dissolved oxygen and high fecal bacteria counts in proximity to anchored vessels. Violations of the State standards for dissolved oxygen and bacteria were common. At the time of the sampling, approximately 400 vessels were anchored in the Harbor during winter months. After designation of state waters as a no-discharge zone, a harbor plan was

from vessels by City of Marathon facilities at Boot Key Harbor and private marinas in Marathon.

Through the diligence of Monroe County and the City of Marathon, Boot Key Harbor is now very well managed and has improving water quality. It is reported that porpoises, mullet, eagle rays, and other marine organisms that were not seen for many years within the harbor are now commonly sighted. Also, fecal bacteria levels have been greatly reduced in surface waters and regularly meet state standards. This is truly a success story.

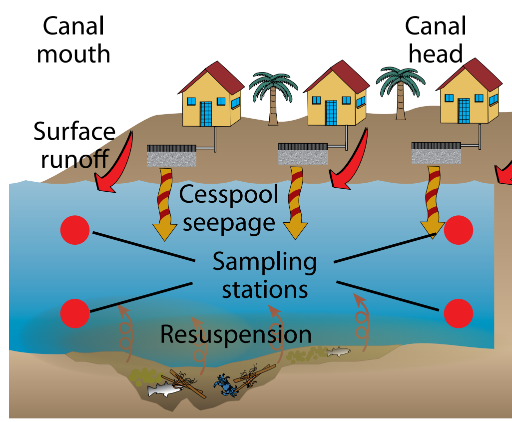
Sewage treatment improvements enhance water quality in Little Venice canals, Florida Keys

Henry O. Briceño and Joseph N. Boyer

Fecal coliform bacteria and enterococci (*Enterococcus* spp.) bacteria live in human intestines, and their presence in surface waters is correlated with fecal contamination and the presence of human pathogens. Testing surface waters, beaches, and shellfish beds for the presence of these bacteria is a routine method for protecting public health.

Historically, many communities in south Florida were built with poorly functioning on-site wastewater treatment systems. Cesspools are holes in the ground that provide no treatment of wastewater, and septic tanks do not function well in areas with high water tables and/or limestone substrates. Both allow untreated wastewater to rapidly infiltrate the groundwater. Canals within residential communities intersect the groundwater and have high nutrient concentrations and elevated concentrations of fecal bacteria and human viruses.

The Little Venice neighborhood in Marathon, Florida, had high development density, a large concentration of cesspools and inadequate septic systems, and poor canal water quality. In 2004, an advanced wastewater collection system and treatment plant was constructed to serve as a demonstration project to assess the effects of central collection and treatment of wastewater on the water quality in the residential canal system of Little Venice. Phase I entailed sampling the canal water quality from 2001 – 2003, before the treatment plant was built. Monitoring was halted during construction (2004) and resumed in 2005 – 2008 (Phase II) to assess changes after improved wastewater treatment (i.e., remediation).



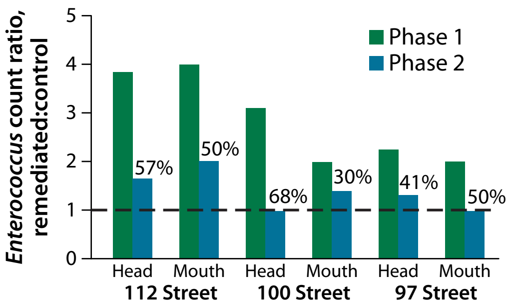
A cross section of a residential canal in Little Venice. Wastewater was deposited into a cesspools beneath houses before remediation. Untreated wastewater entered the canal via groundwater. Organic excrement accumulated in the bottom of canals for many years.

Google Earth

Location of water quality sampling stations (yellow dots) at head and mouth of canals in Little Venice, Marathon, Florida, and offshore control station.

Sampling occurred weekly at the head and mouth of three canals (97th St., 100th St., and 112th St.) scheduled to receive central collection and treatment (remediated), one control canal (91st St.) lacking remedial actions, and a nearshore control site. Weekly measurements included salinity, temperature, nutrients, dissolved oxygen, and fecal coliform and enterococci bacteria counts.

Water quality in the Little Venice area is the result of a dynamic interaction among water masses moving from the Gulf of Mexico to the Atlantic Ocean through Vaca Cut and alongshore, ocean waters, and stormwater runoff. Thus, changes in water quality due to improved sewage treatment practices can be difficult to separate from changes due to natural variation and the occasional influence of remote waterbodies. Additionally, water quality in the canals may be influenced by their depth and length, flushing rates, groundwater seepage, and the accumulation of organic excrement and debris that has collected in the bottom of the canals for many years.



This bar graph compares *Enterococcus* bacteria count ratios between remediated canal sites and the corresponding control site in the 91st St. canal for Phase I (green) and Phase II (blue). Ratios above 1.0 indicate worsening conditions than the control canal, and changes from Phase I to Phase II are shown as percentages of improvement. All stations sampled in the remediated canals show an improvement in bacteria counts after remediation.

Overall, this demonstration project documented that removing cesspools and nonfunctional septic tanks from a waterfront residential neighborhood resulted in a decrease in fecal coliform and enterococci bacteria in adjacent canals by 77% and 57%, respectively, 4 years after remediation. The improvement was greatest at stations that had higher bacterial counts in Phase I.

The heads of canals experience more restricted circulation (flushing) than the mouths of canals, and the heads of canals consistently had higher bacterial counts than stations at canal mouths. Before remediation, 5.2% of weekly counts of enterococci at canal mouths exceeded the recommended safe levels. Three years after houses were connected to the central wastewater collection system, the level of exceedances dropped to 4.0%, and during 2008, they dropped further to 1.6%, a sign of significant improvement.

Improvements to concentrations of bacteria may be masked by the regrowth of the bacteria in the organic-rich and nutrient-rich bottom sediments. So, in addition to comparisons of individual sites between pretreatment and posttreatment, bacteria counts were compared between remediated sites and control sites to filter out effects occurring across the region that may not be related to remediation. These analyses indicate that enterococci count ratios in Phase II decreased significantly compared with the corresponding control sites (30% – 68%), likely due to the improved sewage treatment practices in homes adjacent to the canals.

W. L. Kruczynski - EPA

Little Venice subdivision is a very dense development. Prior to connection to a central collection system and an advanced wastewater treatment plant, most homes discharged sewage into an unlined hole under the house (cesspool), which resulted in high concentrations of fecal bacteria in the canals.

The concentration of dissolved oxygen is an important water quality parameter because it controls the type and number of organisms that can live in the water and the chemistry of other compounds found there (e.g., heavy metals). Prior to remediation, the amount of dissolved oxygen in canals fell below the State Water Quality Standard for Class III marine waters (minimum 4.0 mg/l or daily average 5.0 mg/l) 57% of the time for surface samples and 67% of the time for bottom samples. After remediation, dissolved oxygen exceedances decreased to 49% and 58% for surface and bottom samples, respectively. The high concentrations of organic sediments in the canals may continue to contribute to the slow improvement in levels of oxygen until the canals are fully flushed.

You can help to improve water quality

William L. Kruczynski, Gus Rios, and George Garrett

There are many activities that homeowners, visitors, and local governments can do to improve water quality in canals and other nearshore waters.

Reduce nutrient loading

Nutrients, mainly nitrogen and phosphorus, are important for plant growth. However, too many nutrients leads to problems, such as algal blooms. Because canals, marina basins, and other confined waters have poor circulation and flushing, they are especially susceptible to impacts of excess nutrients.

The following activities will minimize nutrient loading into waters:

- Support implementation of wastewater and stormwater master plans and enforcement of state water quality regulations.
- Maintain septic tanks and drainfields to ensure nutrient uptake.
- Limit application of fertilizers and other chemicals away from canals.
- Create buffer zones adjacent to surface waters and direct drainage away from open water.
- Compost organic wastes or dispose in household garbage, not in canals.
- Replace exotic vegetation with native plants, especially on canal banks.
- Use phosphorus-free detergents.
- Discharge gray water from washing machines, sinks, and showers to approved wastewater treatment systems.
- Comply with no-discharge zone regulations.

Use water efficiently

- Install high efficiency shower heads.
- Fill bathtub with minimal amount of water needed.
- Run dishwasher and clothes washer only when full.
- Keep diapers and other trash out of toilets.
- Turn off faucets when not in use and while shaving and brushing teeth.
- Eliminate plumbing leaks.
- Install aerators in faucets.
- Replace old appliances with high efficiency models.

Increase canal circulation and flushing

Generally, measures to improve circulation and flushing of canals are beyond the means of individuals. However, individuals and homeowner associations can work with local governments to make improvements.

Water quality in dead-end canals can be improved by:

- Backfilling deep canals to shallower depths to facilitate tidal exchange and mixing;
- Aerating canal waters to assist vertical circulation;
- Removing accumulation of organic, oxygen-demanding sediments from canals;
- Installing flushing channels and culverts provided that the action will not degrade receiving waters; and
- Installing floating booms, air curtains, and other devices to prevent floating weeds and other debris from entering canals.

Introduction citations

1. Wikipedia. Water Quality. Available from: http://en.wikipedia.org/wiki/Water_quality (Updated 2 Feb 2011; cited 15 Feb 2011). *Definition of water quality and how it is measured.*
2. Cordy GE. 2001. A primer on water quality. United States Geological Survey. Available from: http://pubs.usgs.gov/fs/fs-027-01/ (Updated 2 Feb 2006; cited 15 Feb 2011). *Definition of water quality and how human activities can affect it.*
3. United States Environmental Protection Agency. Water Quality Criteria. Available from: http://www.epa.gov/waterscience/criteria/ (Updated 20 Jan 2011; cited 15 Feb 2011). *Section 304 (a)(1) of the Clean Water Act requires EPA to develop criteria for water quality.*
4. United States Environmental Protection Agency. Water Quality Standards Handbook: Second Edition. Available from: http://www.epa.gov/waterscience/standards/handbook/ (Updated 29 Dec 2010; cited 15 Feb 2011). *Provides guidance on the development of water quality standards.*
5. United States Environmental Protection Agency. Water Education and Training. Basic Course: Key Concepts (Module 3.e). Forms and Expressions: Numeric and Narrative Criteria. Available from: http://www.epa.gov/waterscience/standards/academy/keyconcepts/mod3/page6.htm (Updated 1 Apr 2010; cited 15 Feb 2011). *Most water quality criteria are expressed as numeric (quantitative) parameters. When pollutants cannot be precisely measured, narrative criteria are used to express a parameter in a qualitative form.*
6. Florida Department of Environmental Regulation. 2011. Fact Sheet about Outstanding Florida Waters. Available from: http://www.dep.state.fl.us/water/wqssp/ofwfs.htm (Updated 19 Feb 2009; cited 15 Feb 2011). *State of Florida Rules and authorites to establish Outstanding Florida Waters because of their natural attributes.*
7. Group of Experts on the Scientific Aspects of Marine Environmental Protection (GESMAP). (1990) The state of the marine environment. United Nations Environment Programme. UNEP Regional Seas Rep Stud 115:1–111. *Eutrophication is one of the major causes of immediate concern in the marine environment. The primary cause is the discharge of nitrogen and phosphorus into coastal waters.*
8. United States Commission on Ocean Policy. 2004. An Ocean Blueprint for the 21st Century. Final Report of the United States Commission on Ocean Policy. Available from: http://www.oceancommission.gov/documents/full_color_rpt/ (Updated 13 May 2005; cited 15 Feb 2011). *Recommendations on stopping degradation of coastal waters.*
9. United States Geological Survey. Water Science for Schools. Water Quality. Available from: http://ga.water.usgs.gov/edu/waterquality.html (Updated 8 Feb 2011; cited 15 Feb 2011). *Sources of pollution to surface water and groundwater.*
10. Kump L. 1998. Fate of wastewater nutrients in Florida Keys groundwater. Final Report, United States Environmental Protection Agency X98429297-0-PA, 107 p. *Movement of injected wastewater into groundwater of the Florida Keys; denitrification; sequestering of phosphate.*
11. National Oceanic and Atmospheric Administration. 2010. Marine Sanitation Device Discharge Regulations for the Florida Keys National Marine Sanctuary. Federal Register 75(227)(November 26, 2010), 15 CFR Part 922, p. 72655-72660. Available from: http://www.gpo.gov/fdsys/pkg/FR-2010-11-26/pdf/2010-29416.pdf (cited 18 Mar 2011). *Federal regulation notice creating a no-discharge-zone in federal waters of the Florida Keys National Marine Sanctuary.*
12. United States Geological Survey. 2000. Mercury in the environment. Fact Sheet 146-00. Available from:http://www.usgs.gov/themes/factsheet/146-00/ (Updated 19 Feb 2009; cited 15 Feb 2011. *The risk of mercury toxicity is determined by the likelihood of exposure, the form of mercury present, and the geochemical and ecological factors that influence how mercury moves and changes form in the environment.*
13. Ludwig A. 1997-2009. Fecal Coliform Bacteria Counts: What they really mean about water quality. Oasis Design. Available from : http://www.oasisdesign.net/water/quality/coliform.htm (Cited 15 Feb 2011). *Discussion of bacterial indicators of water quality, including general coliforms, fecal coliforms, and enterococci bacteria.*
14. Wikipedia. *Enterococcus*. Available from: http://en.wikipedia.org/wiki/Enterococcus (Updated 1 Jan 2011; cited 15 Feb 2011). *The acceptable level of contamination of* Enterococcus *bacteria is very low. Hawaii limits for water off its beaches is 7 colony-forming units per 100 ml of water.*
15. Noble RT, Moore DF, Leecaster MK., McGee CD, Weisberg SB. 2003. Comparison of total coliform, fecal coliform, and *Enterococcus* bacterial indicator response for ocean recreational water testing. Water Res 37(7):1637-1643. *Comparison of the relationship between the bacterial indicators and the effect that bacterial standards have on recreational waters.*
16. Griffin DW, Gibson III CJ, Lipp EK, Riley K, Paul III JH, Rose JB. 1999. Detection of viral pathogens by reverse transcriptase PCR and of microbial indicators by standard methods in the canals of the Florida Keys. Appl Environ Microb. 65: 4118-4125. *Sites in the Florida Keys were tested for bacteria, protozoans, and viruses. Ninty-five percent of sites tested were positive for at least one human virus group even when other indicators were absent. Exposure to canal waters through recreation and work may contribute to human health risks.*
17. State of Florida Statute 99-395. Available from: http://www.monroecounty-fl.gov/DocumentView.aspx?DID=479 (Cited 15 Feb 2011). *State law requiring improvements of wastewater treatment and disposal in Monroe County, Florida.*
18. Szmant AM. 2002. Nutrient enrichment on coral reefs: Is it a major cause of coral reef decline? Estuaries 25:743-766. *Over-enrichment (bottom up) can be the cause of localized coral reef degradation, but the case for widespread effects is not substantiated. Loss of grazers can result in high cover and biomass of fleshy algae.*
19. Futch JC, Griffin DW, Lipp EK. 2010. Human enteric viruses in groundwater indicate offshore transport of human sewage to coral reefs of the Upper Florida Keys. Environ Microbiol. 12:964-974. *Human viruses in groundwater at offshore reef are indicative of subterranean transport system from land.*
20. Lipp EK, Griffin DW. 2004. Analysis of coral mucus as an improved medium for detection of enteric microbes and for determining patterns of sewage contamination in reef environments. EcoHealth 1:317-323. *Human viruses are found in coral mucus.*
21. Florida Department of Environmental Protection. 2011. Land-Bases Sources of Pollution Focus Team. Available from: http://www.dep.state.fl.us/coastal/programs/coral/land-based.htm (Updated 7 Jul 2009; cited 15 Feb 2011). *Local action strategy to identify and resolve land-based sources of pollution in southeast Florida.*
22. Boyd, GR, Reemtsma H, Grimm, DA, Mitra S. 2003. Pharmaceuticals and personal care products (PPCPs) in surface and treated waters of Louisiana, USA and Ontario, Canada. Sci Total Environ. 311:135-149. *Report on the widespread occurrence of pharmaceuticals, hormones, and other organic sewage contaminants in the aquatic environment.*

Water Quality

23. Singh SP, Azua A, Chaudhary A, Kahn S, Willett KL, Gardinali PR. 2010. Occurrence and distribution of steroids, hormones and selected pharmaceuticals in South Florida coastal environments. Ecotoxicology 19:338-350. *Documentation of occurrence and distribution of fifteen hormones and steroids and five common pharmaceuticals in surface waters of south Florida.*
24. Bortone SA, Davis WP. 1994. Fish intersexuality as an indicator of environmental stress. Bioscience 44:165-172. *Human modification of the environment through waste discharge has altered the sexual condition of fishes.*
25. Sumpter JP. 1997. Environmental control of fish reproduction: a different perspective. Fish Physiol Biochem. 17:25-31. *A review of identity of endocrine-disrupting chemicals, their mechanisms of action, and their effects on reproduction of fishes.*
26. Messinger S. 2010. Chemicals in the water are bending genders in wildlife-Is it happening to us too? AlterNet, March 29, 2010. Available from: http://www.alternet.org/water/146222/chemicals_in_the_water_are_bending_genders_in_wildlife_--_is_it_happening_to_us,_too/ (Cited 15 Feb 2011). *Endocrine disrupters are changing the sex of some aquatic organisms, which may continue to find its way into humans later on down the food chain.*
27. Langevin C. 2000. Ground-water discharge into Biscayne Bay. United States Geological Survey, South Florida Information Access. Available from: http://sofia.usgs.gov/projects/index.php?project_url=grndwtr_disch (Updated 1 Feb 2011; cited 15 Feb 2011). *Prior to the construction of the vast canal network in south Florida, offshore springs discharged large quantities of fresh groundwater into Biscayne Bay.*

Further reading

Boyer JN, Fourqurean JW, Jones RD. 1999. Seasonal and long-term trends in the water quality of Florida Bay (1989-1997). Estuaries 22:417-430. *Analysis of six years of water quality data from eastern, central, and western Florida Bay.*

Bricker, S, Longstaff B, Dennison W, Jones A, Boicourt K, Wicks C, Woerner J. 2007. Effects of Nutrient Enrichment In the Nation's Estuaries: A Decade of Change. Harmful Algae 8(1):21-32. *A national assessment of coastal eutrophication. Eutrophication is a widespread problem with 65% of assessed systems showing moderate to high level problems. The most impacted region was the mid-Atlantic.*

Cable JE, Corbett DR, Walsh MM. 2002. Phosphate uptake in coastal limestone aquifers: A fresh look at wastewater management. Limnol Oceanogr Bull. 11:29-32. Available from: http://www.aslo.org/bulletin/02_v11_i2.pdf (Accessed 15 Feb 2011). *Eutrophication is pervasive in aquatic ecosystems throughout the world. The usual suspects in this coastal water quality dilemma are surface inputs, such as sewage effluent, stormwater runoff, and agriculture. In addition to surface water, submarine groundwater discharge may contribute to the transport of nutrients to coastal waters, especially in areas with a high density of sewage disposal and treatment facilities. Phosphate was found to be sequestered by limestone when injected with wastewater.*

CH2MHill. 2000. Monroe County Comprehensive Sanitary Wastewater Master Plan. *Planning document for wastewater improvement for Monroe County, Florida.*

Corbett DR, Kump L, Dillon K, Burnett W, Chanton J. 2000. Fate of wastewater-borne nutrients under low discharge conditions in the subsurface of the Florida Keys, USA. Mar Chem. 69:99-115. *Observations in wells at Long Key, Florida showed that 95% of phosphate and 65% of nitrate injected with wastewater may be removed by adsorption and denitrification respectively.*

Dillon K, Burnett W, Kim G, Chanton J, Corbett DR, Elliott K, Kump L. 2003. Groundwater flow and phosphate dynamics surrounding a high discharge wastewater disposal well in the Florida Keys. J Hydrol. 284: 193-210. *Horizontal and vertical migration of injected wastewater was followed at Key Colony Beach, Florida. Wastewater moved horizontally up to 20 m/day and was highly diluted when it reached surface waters. Phosphate was rapidly adsorbed on limestone until an equilibrium was reached.*

Griggs EM, Kump LR, Bohlke JK. 2003. The fate of wastewater-derived nitrate in the subsurface of the Florida Keys, Key Colony Beach, Florida. Estuar Coast Shelf Sci. 58:517-539. *Path of wastewater injected into groundwater showed a buoyant plume that quickly moved (weeks to months) to surface waters in an adjacent canal with little reduction of nitrate, and a portion with longer residence time in which nitrate was reduced by dilution and denitrification.*

Hu C, Hackett KE, Callahan MK, Andrefouet S, Wheaton JL, Porter JW, Muller-Karger FE. 2003. The 2002 ocean color anomaly in the Florida Bight: A cause of local coral reef decline? Geophys Res Lett. 30, 1151, 4 p. *The observations from satellite ocean color data suggested that a "blackwater" event over reef sites led to the decline in the benthic communities.*

Hu C, Muller-Karger FE, Vargo GA, Neely MB, Johns E. 2004. Linkages between coastal runoff and the Florida Keys ecosystem: A study of a dark plume event. Geophys Res Lett. 31, L15307, 4 p. *A "black water" event off the southwest coast of Florida is tracked by satellite images.*

Hunt J, Nuttle W. 2007. Florida Bay Science Program: A Synthesis of Research on Florida Bay. Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute Technical Reptort TR-11, 148 p. *Summary of ecosystem history, physical processes, nutrient dynamics, plankton blooms, seagrass ecology, and higher trophic level species in Florida Bay.*

Keble CR, Hohns ER, Nuttle WK, Lee TN, Smith RH, Ortner PB. 2007. Salinity patterns of Florida Bay. Estuar Coast Shelf Sci. 71:318-334. *The salinity of Florida Bay has undergone dramatic changes over the past century. Salinity values reached their most extreme, up to 70 ppt, in the late 1980s, concurrent with ecological changes in Florida Bay, including a mass seagrass die-off.*

Lapointe BE, O'Connell JD, Garrett GS. 1990. Nutrient couplings between on-site waste disposal systems, groundwater, and nearshore surface waters of the Florida Keys. Biogeochemistry 10: 289-307. *Significant nutrient enrichment (up to 5000-fold) occurred in groundwaters contiguous to on-site disposal systems.*

Lipp EK, Jarrell JL, Griffin DW, Lukasik J, Jacukiewicz J, Rose JB. 2002. Preliminary evidence for human fecal contamination of corals in the Florida Keys. Mar Pollut Bull. 44: 666-670. *Coral mucus harbors human viruses.*

Nobles RE, Brown P, Rose JB, Lipp EK. 2000. The investigation and analysis of swimming-associated illness using the fecal indicator *Enterococcus* in southern Florida's marine waters. Florida J Environ Health 169:15-19. *Swimmers in the 1999 race around Key West reported water-borne illnesses.*

Paul JH, McLaughlin MR, Griffin D, Lipp EK, Stokes R, Rose JB. 2000. Rapid movement of wastewater from onsite disposal systems into surface waters in the Lower Florida Keys. Estuaries. 23:662-668. *Use of bacteriophages as tracers showed rapid movement of wastewater from injection wells and canals into surface waters. In Boot Key Harbor, Marathon, Florida, tracer placed in a septic tank was found in adjacent canal in 3.25 hours.*

Paul JH, Rose JB, Jiang SC, Zhou X, Cochran P, Kellogg C, Kang JB, Griffin D, Farrah S, Lukasik J. 1997.

Evidence for groundwater and surface marine water contamination by waste disposal wells in the Florida Keys. Water Res 31:1448-1454. *In Key Largo and the Middle Florida Keys, viral tracers appeared after short periods of time in groundwater (8 h after injection) and surface marine waters (10 h and 53 h for Key Largo and the Middle Keys, respectively). Estimated rates of tracer movement were greatest in Key Largo (2.5-35 m/h), where tidal pumping was implicated in tracer movement. These results indicate that wastewater injected into the subsurface can make its way rapidly to surface marine waters, where it may contribute to water quality deterioration.*

Phlips EJ, Badylak S, Lynch TC. 1999. Blooms of the picoplanktonic cycnobacterium *Synechococcus* in Florida Bay, a subtropical inner-shelf lagoon. Limnol Oceanogr. 44:1166-1175. *Seventeen sites in Florida Bay were sampled monthly for 51 months to describe the spatial and temporal patterns of phytoplankton blooms.*

Rudnick DT, Childers DL, Boyer JN, Fontaine III TD. 1999. Phosphorus and nitrogen inputs to Florida Bay: The importance of the Everglades watershed. Estuaries 22:398-416. *Quantification of nutrient inputs to Florida Bay from various sources.*

Schubel J.R. 1981. The Living Chesapeake. Johns Hopkins University Press, Baltimore, MD, 113 p. *Classic work on the ecology and environmental problems of Chesapeake Bay.*

Shinn EA, Reese RS, Reich CD. 1994. Fate and pathways of injection-well effluent in the Florida Keys. United States Geological Survey, Open-File Report 94-276, 116 p. *Analysis of information of samples taken from wells off Key Largo and the Lower Keys on movement of groundwater in the Florida Keys and influence of tidal pumping on sewage effluent injected into over 600 disposal wells.*

Swart PK, Lamb K, Saeid A. 2005. Temporal and spatial variation in the δ 15N and δ 13C of coral tissue and zooxanthellae in *Montastraea faveolata* collected from the Florida Reef Tract. Limnol Oceanogr. 50:1049-1058. *Nitrogen and carbon from sewage may not reach bank reef.*

Wetz JJ, Lipp EK, Griffin DW, Lukasik J, Wait D, Sobsey MD, Scott TM, Rose JB. 2004. Presence, infectivity, and stability of enteric viruses in seawater: relationship to marine water quality in the Florida Keys. Mar Poll Bull. 48:698-704. *Presence of infectious enteroviruses were found during winter at two sites when no sites exceeded recommended levels of enterococci or fecal coliform bacteria.*

Website references

Boyer, J. SERC Water Quality Monitoring Network. Southeast Environmental Research Center, Florida International University. Available from: http://serc.fiu.edu/wqmnetwork/ (Accessed 16 Feb 2011). *Data from water quality monitoring stations in south Florida.*

Corbett DR, Burnett WC, and Chanton JP. A Primer on Submarine Groundwater Discharge: An Unseen Yet Potentially Important Coastal Phenomenon. University of Florida IFAS Extension, EDIS Publication No. SGEB-54. Available from: http://edis.ifas.ufl.edu/sg060 (Accessed 15 Feb 2011). *Groundwater that is contaminated through industrial or agricultural discharge or sewage treatment may eventually become a marine contamination problem.*

Florida Department of Environmental Protection. 2008. Report to the Department of Community Affairs 10-Year Work Program for Monroe County Florida Keys Wastewater Improvements (April 2008). Available from: http://www.dep.state.fl.us/south/Keys/Keys_Report_to_DCA_04-22-08.pdf (Accessed 15 Feb 2011). *Status of wastewater improvements in the Florida Keys, June 2007.*

Florida Department of Environmental Protection. 2011. Florida's Waters: Florida Keys Watershed. Available from: http://www.protectingourwater.org/watersheds/map/florida_keys/ (Accessed 16 Feb 2011). *Water quality is affected by effluent from septic tanks and cesspools, stormwater runoff, and discharges from shallow injection wells that can move through the porous limestone substrate to open waters or canals.*

Florida Department of Environmental Protection. 2011. Surface Water Quality Standards, News and Announcements. Available from: http://www.dep.state.fl.us/water/wqssp/surface.htm (Updated 9 Feb 2011; accessed 15 Feb 2011). *Information on the development of Florida Surface Water Quality Standards.*

Florida Museum of Natural History. South Florida Environments: Florida Bay. Available from: http://www.flmnh.ufl.edu/fish/southflorida/floridabay.html. (Accessed 24 Mar 2011). *Description of habitat types found in Florida Bay.*

Howarth R, Anderson D, Cloern J, Elfring C, Hopkinson C, Lapointe B, Malone T, Marcus N, McGlathery K, Sharpley A, Walker D. 2000. Nutrient Pollution of Coastal Rivers, Bays, and Seas. Issues in Ecology No. 7:1-15. Available from: http://www.epa.gov/watertrain/pdf/issue7.pdf (Accessed 15 Feb 2011). *Summary of how nutrient pollution has degraded coastal waters and strategies to improve the problem.*

MACTEC Engineering and Consulting, Inc. 2003. Monroe County Residential Canal Inventory and Assessment. Available from: http://www.monroecounty-fl.gov/index.aspx?NID=443 (Accessed 6 Sept 2011). *An inventory of the residential canals in the Florida Keys.*

McKenzie, C. Wastewater reuse conserves water and protects waterways. National Environmental Services Center. Available from: http://www.nesc.wvu.edu/ndwc/articles/OT/WI05/reuse.pdf (Accessed 16 Feb 2011). *A comprehensive guide on the benefits of water reuse.*

National Oceanic and Atmospheric Administration. 2007. NOAA report on nutrient pollution forcasts worsening health for nation's estuaries. Available from: http://www.noaanews.noaa.gov/stories2007/s2898.htm (Accessed 16 Feb 2011). *Press release on comprehensive assessment of estuarine eutrophication. Report documents worsening health of nation's estuaries.*

Sewage Treatment. 2009. Artifical sewage treatment. Available from: http://sewagetreatment.us/sewage-treatment/artificial-sewage-treatement-waste-water-sewage/ (Accessed 6 Sept 2011). *A primer on sewage treatment methods.*

Smithsonian National Museum of American History. How the poliovirus works. Available from: http://americanhistory.si.edu/polio/virusvaccine/how.htm (Accessed 26 July 2011). *Pathways of infection and affects of the poliovirus on human nerve cells.*

Spade DJ, Griffitt RJ, Liu L, Brown-Peterson NJ, Kroll KJ, Feswick A, Glazer R, Barber DS, Denslow ND. 2010 Queen Conch (*Strombus gigas*) testis regresses during the reproductive season at nearshore sites in the Florida Keys. PLoS ONE 5(9):1-14. (e12737. doi:10.1371/journal.pone.0012737). Available from: http://www.plosone.org/article/info%3Adoi%2F10.1371%2Fjournal.pone.0012737 (Accessed 15 Feb 2011). *Reproduction of queen conch is inhibited in nearshore areas of the Florida Keys.*

Stewart, R. 2005. Introduction to Coastal Pollution. In: Oceanography in the 21st Century- An Online Textbook. Department of Oceanography, Texas A&M University. Available from: http://oceanworld.tamu.edu/resources/oceanography-book/introtocoastalpollution.htm (Updated 3 Aug 2009; accessed 16 Feb 2011). *An introduction to the problem* *of coastal pollution. Book also includes chapters on Sources of Coastal Pollution, Invasive Species, Harmful Algal Blooms, Oil Spills, and Coastal Pollution Policy.*

Stewart, R. 2005. Sources of Coastal Pollution. In: Oceanography in the 21st Century-An Online Textbook. Department of Oceanography, Texas A&M University. Available from: http://oceanworld.tamu.edu/resources/oceanography-book/sourcesofcoastalpollution.htm (Updated 15 Apr 2009; accessed 16 Feb 2011). *Summary of point and nonpoint sources of coastal pollution.*

United States Environmental Protection Agency. 2005. A Homeowners Guide to Septic Systems. EPA-832-B-02-005. 15 p. Available from: http://www.epa.gov/own/septic/pubs/homeowner_guide_long.pdf (Accessed 28 Apr 2011). *General information on conserving water and maintaining a septic tank system.*

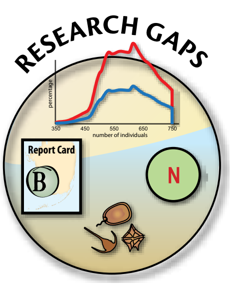
United States Geological Survey. Water Science for Schools. A visit to a Wastewater-Treatment Plant: Primary Treatment of Wastewater. Available from: http://ga.water.usgs.gov/edu/wwvisit.html (Updated 8 Feb 2011; accessed 16 Feb 2011). *A summary of steps in the treatment of wastewater.*

Walker W. 1998. Estimation of inputs to Florida Bay: Inputs from Florida mainland- flows. Available from: http:www.wwwalker.net/flabay/enpflows.htm (Updated 30 Mar 2002; accessed 10 Mar 2010). *Detailed quantitative analysis of water movement from the Florida mainland to Florida Bay.*

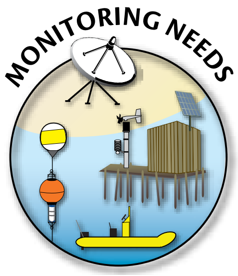
4. CORAL REEFS AND HARDBOTTOM HABITATS

Coral Reefs and Hardbottom Habitats Chapter Recommendations

- Coordinate management efforts to identify and **reduce local, regional**, and **global stressors** to corals and coral reefs.
- Develop an effective and strategic approach to inform the public of the **implications of climate change** on coral resources, garner their support in passing legislation and regulations to reduce carbon emissions, and share the responsibility of improved stewardship of reef resources.
- Promote establishment of **Marine Protected Areas** and special management zones to maximize the ability of a reef ecosystem to recover from human and natural disturbances. Because not all of the functions of all the species on a reef are fully known, it is prudent to protect them all for the benefit of the whole.
- Establish and increase **mooring buoy programs** to limit damage from anchoring on coral reefs and hardbottom habitat.
- **Secure funding support** for education and effective communication on best management practices for diving, snorkeling, and fishing around coral reefs.
- **Implement science-based fishing regulations** to allow recovery of depleted fish stocks and protect key species from overfishing.



- Identify causes and methods of transmission of **coral diseases** and the role of multiple stressors affecting reef health.
- Quantify the role of **microorganism communities** in coral health and resilience.
- Differentiate between **natural variation** in coral abundance and human-induced changes.
- Conduct controlled experiments to identify factors affecting **recruitment** rates in stony corals.
- Quantify the role of **hardbottom communities** in the structure and function of the south Florida marine ecosystem.
- Determine the role of **genetic variability** and connectivity among sites and regions related to coral recruitment, survival, and longevity.
- Identify and assess genetic components of corals **resilient to bleaching** and other diseases and culture them for use in restoration projects.
- Conduct socioeconomic studies to regularly assess the **ecosystem values** provided by natural and artificial reefs.
- Quantify the effects of **ocean acidification** on coral growth and health.



- Continue monitoring of **abundance and diversity** of coral reef organisms.
- Quantify factors controlling successful **coral recruitment** patterns.
- Monitor annual changes of **coral disease patterns** throughout the region and identify "hot spots" of occurrence.
- Monitor **artificial reefs** to evaluate whether intended objectives are being met.

Chapter title page: Sherwood Forest, Dry Tortugas. J. Luo, UM/RSMAS.

Introduction

What are corals?

Corals are bottom-dwelling marine animals that are related to sea anemones and jellyfish. Common corals are actually colonies composed of individual polyps. A polyp is a cup-shaped unit composed of a mouth located at the apex of a stalk that is surrounded by tentacles.[1] Polyps resemble sea anemones in structure. There are two main groups of corals: hard corals and soft corals.

Hard corals, or stony corals, are comprised of polyps that have six tentacles, or multiples of six.[2] Polyps of hard corals secrete a rigid skeleton made of calcium carbonate that they extract from seawater. The polyps live on the surface of the skeleton and excrete a protective mucus layer. There are two major growth forms of hard corals: branching corals and boulder corals. Branching corals in south Florida include elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*). Common boulder corals in south Florida include boulder star coral (*Montastraea annularis*) and grooved brain coral (*Colpophyllia natans*). Not all corals form coral reefs; those that do are called hermatypic hard corals. Hermatypic corals harbor symbiotic algae (zooxanthellae) within the polyp cells that give them their various colors.[3,4] Elkhorn coral, boulder star coral, and grooved brain coral are examples of reef-forming corals.


J.W. Porter - UGA

Hard (i.e., stony) corals, such as this pillar coral, consist of a colony of individual polyps that excrete a calcium carbonate skeleton. Each polyp has a multiple of six tentacles.

Soft corals are also called "octocorals" because their polyps have eight tentacles, or multiples of eight. Most soft corals secrete a flexible skeleton that consists of a core made from a protein called gorgonin and surrounded by an outer layer that contains the polyps. Soft corals are also known as "gorgonians" because of their inner core.[2]


D.S. Gilliam - NSU

Soft corals (i.e., octocorals) consist of polyps surrounding a flexible core. Each polyp has multiples of eight tentacles.

Hard corals were originally classified by Carl Linnaeus, the founder of modern taxonomy, as "Zoophyta", meaning "animal plants" because they had characteristics of both.[5] Hard corals can feed on planktonic prey that they capture by their tentacles. The tentacles contain stinging cells called nematocysts that are triggered by touch and pierce their prey; then the tentacle delivers the prey item to the polyp mouth. Most corals extend their tentacles at night for feeding.

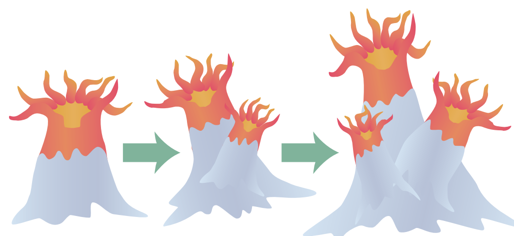
Hard coral polyps are translucent animals that get their colors from the zooxanthellae algae that live within the polyps. Zooxanthellae are microscopic, single-celled algae that contain chloroplasts and carry out photosynthesis in the presence of sunlight. Coral polyps and their zooxanthellae live in a mutualistic symbiotic relationship in which both partners benefit. This coral-algae partnership is extremely efficient, and more than 90% of the organic materials that the algae produce are used by the coral for growth and other metabolic needs.[6] The coral supplies the algae with carbon dioxide and nutrients. Corals actually control the numbers of zooxanthellae within their tissues by limiting the amount of nitrogen they supply to the algae. About one third of the sugars received from the algae is used to produce the protective mucus layer of the coral.[4,6]

Many of the shallow reef-dwelling soft corals have symbiotic algae. Soft corals also feed by capturing small prey in their mucus nets and with their harpoon-armed tentacles.

J. Luo - UM/RSMAS

Coral reefs are found in tropical and subtropical oceans where water is shallow and clear enough to allow sufficient sunlight to penetrate to the bottom.

Corals and the coral reefs that they form provide an interesting paradox: well-developed coral communities are found in the most nutrient-deficient waters of the world. Hard corals need a lot of energy to build their skeletons faster than waves or bioeroding organisms can wear them away. Coral communities are highly productive. It is the partnership between hard corals and their symbiotic algae that allows corals to live in a nutrient-poor environment where sunlight is a plentiful source of energy and planktonic food is generally limited.[4] Coral communities efficiently recycle and preserve organic matter, and that efficiency allows corals to outcompete other organisms in oligotrophic (low nutrient) waters. Efficient recycling of nutrients helps to explain how primary productivity of coral reefs can exceed productivity of areas where nutrients are more abundant.[6]



A coral polyp divides by asexual budding to create a coral colony.

Hard corals can reproduce sexually. In some (brooders), fertilization takes place within the polyp. In others (broadcast spawners), fertilization takes place in the water column. Fertilization results in an embryo and eventually a planula that is distributed by ocean currents. Planulas can attach to suitable substrate and form a polyp. The polyp then divides by asexual budding and creates a colony that acts as a single organism. The limestone skeletons produced by each polyp interconnect. Coral colonies can also propagate through a process of fragmentation when a broken piece of colony can grow a new clone. Branching corals frequently propagate by fragmentation after being broken-up by hurricanes and strong waves or other physical damage.

Coral reef formation

Some, but not all, corals have the ability to join other coral colonies to form spectacularly diverse limestone communities called coral reefs. Some coral reefs on Earth today began growing over 50 million years ago, and some fossil reefs similar to present-day reefs have existed since the age of the dinosaurs (150 million years ago).[7] Coral reefs are found in tropical and subtropical oceans where water is shallow and clear enough to allow sufficient sunlight to penetrate to the bottom and where water temperature is between 18° – 36°C (64° – 97°F); optimal reef growth occurs between 26° – 28°C (79° – 82°F).[8] The adaptation to nutrient-deficient conditions also includes a dependence on adjacent mangrove and seagrass communities to intercept nutrients and sediments from land before they reach the reef. Mangrove and seagrass communities also provide nursery and foraging areas for some animals that dwell on the reef.

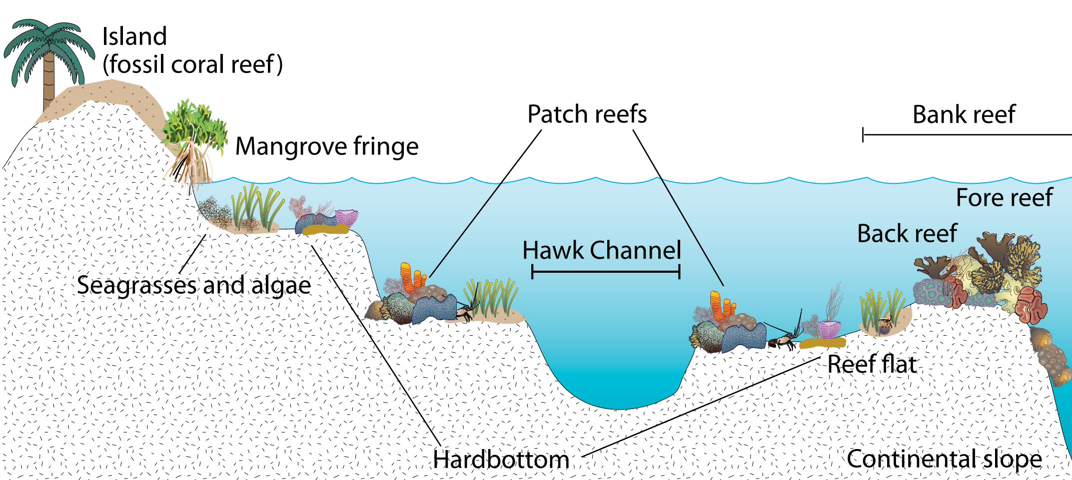
Living coral reefs in south Florida (i.e., Holocene reefs) are about 6000 – 8000 years old and formed when sea level stabilized after the last Ice Age. The two coral species most responsible for Holocene (modern-day) reef building in south Florida are elkhorn coral (*Acropora palmata*) and star coral (*Montastraea annularis*); other colonizing species add to the framework set down by those species.[9,10]

Only the outer layer of a reef is alive. As coral colonies grow and expand and new corals settle, they build their skeletons on top of dead corals from earlier generations. The growth rate of coral reefs in the Keys has been measured by coring through the reef foundation; vertical reef growth rate varies between approximately 0.65 – 4.85 meters (2 – 16 feet) per 1000 years.[9,11]

Geographic distribution of corals

Different coral formations are found throughout south Florida. From about Cape Canaveral to Fort Pierce, the ivory tree coral (*Oculina varicosa*) occurs in banks at about 70 – 100 m (230 – 328 ft) or deeper and can form pinnacles up to 30.5 m (100 ft) tall. Because light levels are low at those depths, the primary food source for the benthic community is phytoplankton and detritus. Like shallow water reef corals, *Oculina* banks provide habitat for a great diversity of fish and invertebrates, including economically important species. Because of heavy fishing pressure and impacts from trawling, the *Oculina* bank off Fort Pierce has been designated a Habitat Area of Particular Concern and is closed to snapper, grouper, and rock shrimp fishing.[10,12]

The area between St. Lucie Inlet and Cape Florida (Key Biscayne, Miami)



From Cape Florida to the Dry Tortugas, corals occur on hardbottom habitats, patch reefs, and deep and shallow bank reefs. Hardbottoms are dominated by octocorals, algae, sponges, and scattered hard corals. Patch reefs have high diversity and coverage of octocorals and hard corals and are generally circular in shape. Bank reefs occur at the edge of the continental shelf in a high-energy environment and have high relief and high hard coral coverage and diversity.

contains the Southeast Florida Reef System. From St. Lucie Inlet to Palm Beach County, elements of tropical coral reef biota occur and become more abundant toward Cape Florida. Staghorn coral (*Acropora cervicornis*) thickets have recently become common in this area. The reefs found in this area are characterized as an octocoral- and sponge-dominated community, with scattered hard corals growing on terraces of fossilized coral reefs built predominantly by elkhorn coral approximately 4000 years ago.[10] Colonies and thickets of staghorn and elkhorn corals as well as boulder corals are found in this area.

The area south and west of Cape Florida is characterized by three main types of coral habitats—hardbottoms, patch reefs, and bank reefs—that are collectively known as the Florida Keys Reef Tract.[10] It is the only shallow water coral reef habitat found on the continental shelf of North America. It is the third longest barrier reef in the world and can be seen from outer space. Hardbottom habitats generally are found close to shore and are dominated by octocorals, sponges, and algae and have low coverage of hard coral species. Patch reefs have high biodiversity of octocorals and hard corals, are generally circular in shape, and have a vertical relief of a few meters. Patch reefs are generally found in waters less than 10 m (33 ft) deep.[9] In the Florida Keys, they are found close to shore and seaward of Hawk Channel in a mosaic of habitats, including seagrasses and hardbottom communities. Patch reefs are the principal reef type between Elliott Key and Key Largo where several thousand patch reefs are found.[13]

Bank reefs occur as a discontinuous band parallel to the Florida Keys island chain and flank the edge of the continental shelf. Bank reefs can be divided into shallow and deep reef zones. The shallow portion of the bank reef occurs in a high-energy environment (wave action) and is dominated by branching corals, fire coral (*Millepora* spp.), and the colonial zoanthid *Palythoa*


F. Charpin - reefguide.org

As corals have disappeared, a colonial zoanthid (*Palythoa*) has increased in dominance at bank reefs.

caribaeorum. The deep bank reefs consist mostly of large boulder corals, barrel sponges, and octocorals. Bank reefs exist in a continuous line south of Cape Florida to the Dry Tortugas.[9,10,13] Bank reefs are found 7 – 13 kilometers (4.4 – 8 miles) seaward of the Florida Keys and have a spur-and-groove structure characterized by elongated sections of reef with high vertical relief (spurs) separated by deeper sandy areas (grooves). Spurs and grooves are oriented perpendicular to shore.[14,15]

In the Upper Keys and in Miami, large islands act as barriers to waters from Biscayne Bay and Florida Bay and have supported the development of extensive offshore reefs seaward of Elliott Key and Key Largo. The Middle Keys are smaller islands that are separated by wide channels connected to Florida Bay and have limited reef development. The islands of the Lower Keys provide some protection to water transport from the Gulf side of the Keys, and the reef development is extensive. Major bank reefs in the Florida Keys include: Carysfort, The Elbow, Key Largo Dry Rocks, Grecian Rocks, French, Molasses, Alligator, Tennessee, Sombrero, Looe Key, American Shoals, Eastern, Middle, and Western Sambos, Eastern and Western Dry Rocks, Rock Key, and Sand Key.[10]

Off the west coast of south Florida, there are no three-dimensional tropical coral reefs. Ledges and outcroppings of limestone are colonized by an assemblage

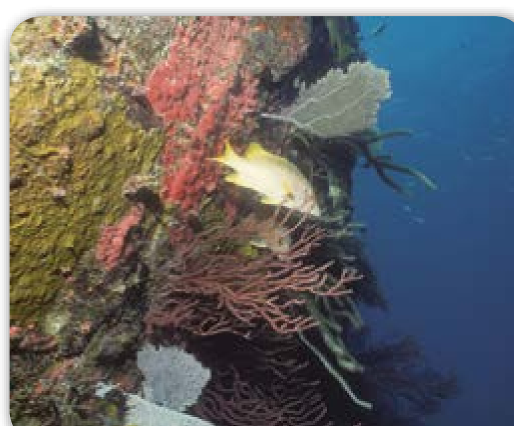
Two coral spurs separated by a light-colored groove (left). Spur-and-groove reefs are a common feature of windward shores of islands, likely because of the continued effects of erosion caused by swell and trade wind waves. The topography of these structures consists of parallel linear spurs (ridges) of active coral growth separated by grooves (depressions) of accumulated sediments and coral debris. Spurs and grooves are oriented perpendicular to shore (right).

of hardy corals, such as knobby star coral (*Solenastrea hyades*) that are capable of living in more turbid water than reef-building corals. The Florida Middle Grounds is a hardbottom community growing on a fossil reef formation located approximately 150 km (93 mi) northwest of Tampa Bay. It has relatively high coral diversity and coverage, but is not an active, three-dimensional reef comparable to those found in the Florida Keys.[10]

Artificial reefs

Artificial reefs are humanmade underwater structures that are constructed by placing materials on the seafloor. They can be made from a variety of hard materials including concrete rubble, rocks and boulders, engineered concrete artificial reef modules, carefully cleaned and prepared steel vessels, and other environmentally suitable artificial reef materials. Shipwrecks are the result of unintentional sinking or mishap resulting in unplanned humanmade marine structure. A main purpose of planned artificial reefs is to provide a hard, stable surface to which algae and other encrusting organisms, such as barnacles, oysters, and corals, can attach. The three-dimensional structure of an artificial reef and the encrusting community of marine life provide structure and food for a diverse assemblage of fish. Artificial reefs may remove some burden of divers, snorkelers, and fishermen from natural reefs. Three ships were sunk in the Florida Keys National Marine Sanctuary for that purpose, one each in the Upper (USS *Spiegel Grove*), Middle (*Adolphus Busch*), and Lower (USNS *General Hoyt S. Vandenburg*) Keys. These wrecks and the many others that exist in south Florida are popular dive spots.

Artificial reefs have also been constructed as compensatory mitigation for hardbottom or reef habitats that were lost through construction projects, including beach nourishment, and vessel groundings. The success of mitigation reefs is measured by their ability to mimic the natural hardbottom



In 1942, the merchant vessel *Benwood* ran aground in the Upper Keys near French Reef and Dixie Shoals. The steel hull of the vessel is colonized by corals, sponges, and algae. The *Benwood* is one of nine sites within the Florida Keys National Marine Sanctuary Shipwreck Trail.

environments that they are intended to replace. Quantitative monitoring at one constructed limestone boulder reef in Broward County revealed that hard and soft coral abundance, diversity, and average size were nearly equal to those found on the natural nearshore hardbottom 5 years after construction.[16] Additional monitoring is needed to conclusively demonstrate that artificial reefs constructed as mitigation provide the same habitat value as the affected natural substrates.

Coral reefs are ecologically and economically important

Coral reefs have ecological and economic values, and the Earth would likely be a less interesting place to live and play if coral reefs did not exist. The three-dimensional structures of coral reefs harbor an amazing biodiversity of plants and animals. They cover less than 1% of the ocean floor, but support about 25% of all marine creatures.[17] About one third of the marine fish (about 6000 – 8000 species) in the world are estimated to live only on coral reefs.[18,19] They provide habitat for numerous species of invertebrates, including mollusks, sponges, sea urchins, starfish, crustaceans, worms, and many other taxonomic groups. Coral reefs are known as the "tropical rain forests of the sea" because of the richness and abundance of species contained in such relatively small areas.[20]

In nature, there are no useless, superfluous life forms. Every life form plays a role in maintaining the ecological integrity of the planet. Maintenance of biodiversity is important because greater species diversity ensures natural sustainability for all life forms. Loss of biodiversity can change ecosystem form and function. Healthy ecosystems that support a full suite of species that characterize the ecosystem are better able to withstand and recover from a variety of disasters. The extirpation of even a single species can have major ecological significance.[21] For example, the loss of the long-spined sea urchin from south Florida reefs is believed to be directly responsible for increased macroalgal growth and decreased coral recruitment. Because not all of the functions of all the species on a reef are fully known, it is prudent to protect them all for the benefit of the whole.

On a global scale, the number of people using coral reefs for subsistence and pleasure has not been adequately quantified, although many small tropical countries are completely dependant on coral reef resources. A healthy coral reef community benefits society in many ways, including protection of shores from impacts of waves and storms; provision of organisms used for food, medicines, and biotechnological advances; and tourism.[21] An example of the value of coral reefs in the development of medicines is azidothymidine (AZT), a treatment for people with HIV infections that is based on chemicals found in a reef sponge.[22] Corals are also an integral part of the global carbon cycle; they remove carbon dioxide, a greenhouse gas, from ocean water and sequester it in coral skeletons and reefs.[11,23]

The economic value of reefs, both artificial and natural, in southeastern Florida (Martin, Palm Beach, Broward, Miami-Dade, and Monroe Counties) was studied in 2001.[24] Reef values were calculated two ways: 1) by assessing "use" of the reefs as person-days spent snorkeling, fishing, or diving and 2) as the expenditures, or dollars, spent to visit the reefs that may include charter boat fees, fuel, bait, tackle, ramp and marina fees, lodging, food, beverages, and equipment rental. The report concluded that 28.8 million person-days were spent using natural and artificial reefs in the five-county region during 2001. Additionally, expenditures for fishing, snorkeling, and SCUBA diving on artificial and natural reefs in the five counties totaled an estimated $3.0 billion per year.[24]

Another value of coral reefs to humankind is knowing that they, as other wild and natural areas on Earth, simply exist. Many people who have never seen a coral reef in person take solace in the fact that coral reefs exist and are teeming with diverse wildlife. They may formalize their support for the continued existence of coral reefs or other wild places by joining and supporting conservation organizations and purchasing speciality license plates, such as Florida's "Protect Our Reefs" plate. Although little empirical work exists on valuation measures of reefs by nonusers and groups distant to coral reefs, studies have suggested that nonuser and distant groups should be included in valuations because of their unflinching support for conservation of all things wild or coral reefs in particular.[25]

NPS

Snorkeling over coral reef and hardbottom habitats is a popular recreational activity in south Florida.

Factors that control the distribution and abundance of corals and coral reefs in south Florida

Different coral species have different ecological requirements. Several species of corals are able to grow and thrive in the more turbid waters of southwest Florida and in Florida Bay. However, they typically occur as isolated colonies and do not construct reefs. Among these corals are the knobby star coral (*Solenastrea hyades*), starlet coral (*Siderastrea siderea*), and robust tree coral (*Oculina robusta*). The southeast coast of Florida has a much more diverse coral community, and healthy growth depends on several interrelated environmental factors, including warm, clear tropical water; normal sea-strength salinity; adequate light penetration; low inorganic nutrients and turbidity; low sedimentation; and vigorous water movement. The role of the Florida Current in providing the proper environmental conditions for coral growth and survival in southeast Florida cannot be overemphasized. It is the influence of the Florida Current and its eddies in shallow waters that allows the temperatures, salinity, and water clarity that are required for coral growth and reef formation. It moderates winter temperatures and provides nutrients, plankton, food sources, and recruitment from remote geographic areas.[10]

South Florida is at the northern latitudinal limit of extensive reef growth in North America, and minimum winter temperature provides the main control of coral reef distribution. Coral reefs cannot form where seawater temperature falls below 18°C (64°F) for extended periods. Corals can generally withstand temperatures as high as 30°C (86°F). An extreme winter cold spell in 1977 in south Florida resulted in widespread death of staghorn corals. In January 2010, a prolonged cold spell resulted in the death of 200- to 300-year-old boulder star corals at shallow patch reefs.[26] The impacts of that cold spell on the Florida Keys Reef Tract are still being evaluated.

Most corals require a stable salinity within a range of 30 – 40 parts per thousand (ppt) salt, and that requirement restricts reef growth near shorelines because freshwater runoff can dilute ambient salinity. The stable-salinity requirement and narrow band of temperature tolerance also result in reduced growth in tidal passes between the islands of the Florida Keys because of the influence of water from Florida Bay that is variable in both temperature and salinity.[27]

Adequate light, nutrients, and turbidity are expressions of clear water. If corals receive too little light, the zooxanthellae cannot photosynthesize efficiently, and coral polyp feeding cannot make up the lost energy required for growth.[22,28] Shading by turbidity and phytoplankton blooms because of a high amount of nutrients in the water column is a cause of decreased light penetration. Reef growth in the Florida Keys can occur to about 30 m (98 ft), and hermatypic corals can survive to about 40 – 45 m (131 – 148 ft).[10] Sediments suspended in the water column decrease light penetration and can settle, smother coral colonies, and impair feeding. Energy used by coral polyps to remove sediments is energy lost from growth and reproduction.

Stressors of corals

South Florida coral reefs are affected by local (e.g., land-based sources of pollution), regional (e.g., water drainage and delivery), and global (e.g., climate change) stresses caused by humans and natural events. Hurricanes, El Niño, coral grazers and degraders, and diseases are natural threats that corals have faced for millennia. It appears that the effects of natural threats may be compounded by stresses caused by humans. Human-induced stressors include overfishing, coastal development, physical impacts by divers and snorkelers, vessel groundings, harvesting of live rock, and dredge-and-fill projects. Global climate change is a human-induced threat to coral reefs worldwide that may ultimately override impacts from other stressors.[22]

Severe hurricanes can detach, overturn, and kill corals due to high wave activity, but results of individual storms have generally been found to be localized to individual reefs. Storms can also fragment branching corals and result in their propagation and expansion in distribution.

Overfishing causes imbalances in community structure. Fishing usually results in the removal of large, predatory fish that can result in increased populations of smaller fishes. Some smaller fish (e.g., three-spot damsel fish) nibble on corals, and when populations increase without checks and balances, corals can suffer. In this case, three-spot


NPS

Given enough time and under healthy growing conditions, staghorn coral that has been broken by the wave action of hurricanes regenerates itself through a process called asexual fragmentation.

damsel fish usually feed on faster-growing elkhorn corals, but with the loss of elkhorn corals due to diseases, damsel fish now feed on slower-growing boulder corals that cannot keep up with their grazing pressure and can die.[29] Destructive fishing practices (e.g., poisoning, blasting, fish traps) are not legal in south Florida, but vigilant enforcement is required.

Trap fishing is permitted in south Florida for blue crabs, stone crabs, and spiny lobsters. Stone crab and spiny lobster traps are constructed of wood or plastic and are weighted by a poured concrete slab that keeps the trap on the seafloor. Placement of traps on seagrasses, hardbottoms, and coral reefs can result in crushing or otherwise destroying valuable benthic habitats. Once traps become lost or abandoned, they may "ghost fish", that is, continue to trap marine organisms until traps degrade enough to allow escape. Lost and abandoned traps visually pollute, damage sensitive habitats, and become hazards to navigation.[30] Traps may become abandoned for several reasons: they can move during storms, making them difficult to locate; they may be snagged by passing vessels and dragged to another area; or, they may be illegally abandoned by their owners. The Florida Fish and Wildlife Conservation Commission has two programs dedicated to removing lost and abandoned traps from state waters. The Spiny Lobster, Stone Crab, and Blue Crab Trap Retrieval Program contracts commercial fishermen to remove abandoned traps from state waters during closed seasons, and the Derelict Trap Retrieval and Debris Removal Program provides a mechanism to authorize volunteer groups to collect derelict traps and trap debris during open or closed seasons.[31]

Increases in several abiotic factors that control coral growth and abundance (salinity, light, low turbidity, and nutrients) can be affected by coastal development. Land clearing can cause increased turbidity and nutrients in surface waters. Coastal construction can result in the removal of mangroves and seagrasses that filter out nutrients and sediments before they reach reefs. When nutrients are added to receiving waters, water clarity is reduced, and faster-growing phytoplankton and benthic seaweeds can outcompete, smother corals, and eliminate settling habitat for coral larvae. Pollution from land has also been implicated in at least one coral disease, white pox.[32]

The biggest threat to corals on a global scale is increasing seawater temperature. When temperature rises above a critical threshold, zooxanthellae are expelled from corals, causing them to appear white (i.e., coral bleaching).[22,33] Bleached corals are stressed not only from the temperature, but also from the lack of food provided by their zooxanthellae partners. Prolonged bleaching can lead to other diseases and coral death.

A recent study has shown that regulating wastewater discharge from the land may help coral reefs to resist climate change. Corals living in cleaner water with fewer nutrients survived better during hot periods than corals in water with higher nutrients that became diseased and bleached.[34] In the face of climate


NOAA

Bleached corals have a white appearance because of the loss of symbiotic algae (zooxanthellae) that give coral their color.

change and ocean warming, that study gives managers hope that maintaining high water quality can improve survival of corals. However, proximity to potential sources of stressors is not always an adequate proxy for assigning risks to reef health. Coral cover, size, growth, and mortality are not always directly related to water quality gradients.[35]

Global temperature is rising because of increased greenhouse gases in the upper atmosphere that form a "blanket" around the Earth. Activities such as burning fossil fuels, changes in land use, and reduction of forest cover result in increased atmospheric concentrations of CO_2 and other greenhouse gases. Increased CO_2 in the ocean can also reduce the ability of corals to secrete limestone skeletons, making them more fragile and slowing their growth.[22,36]

Management

The ecological and economic values of corals and coral reefs to south Florida have long been recognized. Important management actions are in place to help sustain and improve coral resources. The designation of the Florida Keys National Marine Sanctuary provides a management plan that promotes conservation while allowing multiple uses of the resource. A key element is the designation of Marine Protected Areas (MPAs). Setting aside areas where the coral community is left alone (i.e., no-take MPAs) has resulted in larger size and abundance of fishes (e.g., groupers, snappers) and lobsters within the MPAs at Western Sambo (Lower Keys) and Dry Tortugas, as well as in other areas around the world.[37] When allowed to recover, corals attract fish, and fish "spill over" outside the boundaries of the MPAs can improve fishing. MPAs can also provide a control of uses by multiple and often competing user groups of the resource.[38]

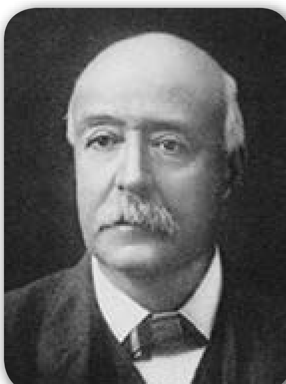
Improving defensible, sustainable fishing regulations; restoring historically lost habitats; and requiring improved wastewater and stormwater treatment and disposal practices will reduce stressors to the coral reef community. In south Florida, many agencies and academic institutions work together to promote wise stewardship of these resources, including regulatory, research, enforcement, and management agencies.

Probably the most important way to reverse damage to our coral reefs is to reduce the emission of greenhouse gases to stem global warming.[22] This may be the hardest stressor to address because it requires informed national and global cooperation. However, just because it is difficult does not mean that global warming can be ignored by governments or individuals. Understanding the importance of coral reefs to Earth and the threats that they face is the first step toward finding workable solutions.

Louis and Alexander Agassiz pioneered coral reef research

Walter C. Jaap

Louis and Alexander Agassiz, their students, and technicians pioneered marine research, particularly in taxonomy and the distribution and abundance of animals found on Florida coral reefs. The father and son were stirred by a raging argument among scientists that stemmed from the 1842 Charles Darwin book that discussed the formation and origins of coral reefs. Alexander passionately pursued an alternative explanation to Darwin's theory of seafloor subsidence to explain coral reef origins and development.

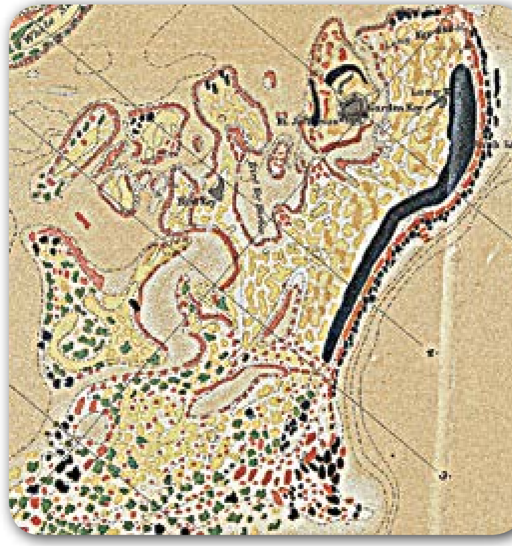


National Academy of Science Archives

Alexander Agassiz, ca. 1850.

In the 1800s, the U.S. government regarded coral reefs as an impediment to shipping and considered using explosives to destroy them in order to avoid the many shipwrecks common in Florida waters. Louis proposed that rather than destroying the reefs, a series of lighthouses be installed along the reef to warn mariners of their locations. That recommendation was adopted, thus saving an important ecosystem from wholesale destruction.

One of Alexander's greatest contributions to coral reef science was completing a comprehensive map of the Dry Tortugas, one of the earliest known maps in the world that provided estimates of coral reef habitats. He surveyed approximately 160 km^2 (100 mi^2) of seafloor in 1881 using a sextant to determine location, a glass-bottomed bucket to make observations, and a lead line to determine depth and sea bottom characteristics.



NOAA

A portion of the seafloor map surrounding Garden Key, Dry Tortugas, prepared by Alexander Agassiz in 1881. This is one of the earliest coral reef habitat maps showing distribution and abundance of corals. It was produced with simple tools: a glass-bottom bucket and a lead line.

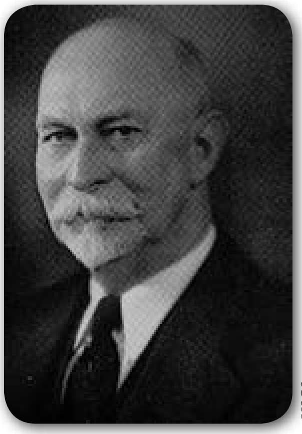
K. Anderson -www.lighthousefriends.com

Between 1833 – 1841, 324 vessels were lost on Florida Keys reefs, 63 at Carysfort Reef. Carysfort Lighthouse was constructed in 1852, one of the lighthouses constructed as a result of Agassiz's recommendation.

Alfred Mayor and Thomas Vaughan expanded coral reef research in south Florida

Walter C. Jaap

One of the most heroic and charismatic early coral reef researchers was Alfred Goldsborough Mayor. A student of Alexander Agassiz, Mayor convinced the Carnegie Institution to build and fund a marine laboratory on Loggerhead Key, Dry Tortugas. The Carnegie Laboratory was opened in 1905 and supported many disciplines of science. Virtually all of the studies were published in the Papers of the Tortugas Laboratory, and Mayor edited each article. Mayor was not only a scientist, but also a talented artist, sailor, fundraiser, and leader. His personal contributions were the taxonomy and systematics of jellyfish and physiological research on thermal tolerance of tropical marine animals (coral bleaching). In addition, Mayor was a hands-on scientist who actually put on dive gear to study coral reefs in Dry Tortugas and Samoa. He died of tuberculosis on Loggerhead Key in 1922, but the Carnegie Laboratory that he founded continued to function until 1939.



USGS

Thomas Wayland Vaughan, ca. 1900.

A. Mayor collection

Alfred Goldsborough Mayor (1868 – 1922) at the wheel of *Physalia*. Mayor changed his name from Mayer in 1918.

Mayor's colleague, geologist Thomas Wayland Vaughan, was interested in the underlying history of coral reefs. In later life, he founded Scripps Institution of Oceanography. His work at the Carnegie Laboratory included the study of fossil records and modern status of Florida and Caribbean reef systems. Vaughan conducted growth rate studies on many corals species and compiled and published seawater temperatures at lighthouses along the Florida Keys Reef Tract for a 25-year period. This is one of the best historical climate records in Florida.

A. Mayor collection courtesy of W. Jaap.

A. Mayor collection courtesy of W. C. Jaap

Loggerhead Key, Dry Tortugas, ca. 1910.

J. W. Wells courtesy of W.C. Jaap

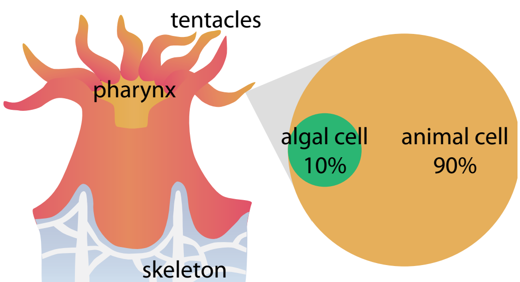
Research diver at Dry Tortugas, ca. 1930.

Corals are amazing creatures

James W. Porter

Are corals animal, vegetable, or mineral?

For all other creatures on the planet, the answer is one of these; but corals are animals that have characteristics of all three! Corals have been described as sea anemones that have a paperweight skeleton. Only 1% of the total weight of coral is living tissue, and the remainder is the skeleton. The animal tissue cells contain symbiotic algae, called zooxanthellae. Symbiosis means unlike organisms living together. The symbiotic algae are single-celled plants that give corals their color.



Corals are made up of individual polyps. They differ from their closest relatives, sea anemones, in their ability to produce a calcium carbonate (i.e., limestone) skeleton. Algal cells live within the coral cells in a mutualistic symbiotic relationship, where both partners benefit.

Did you know?

Corals were misclassifed by the founder of modern taxonomy, Carl Linnaeus, who described them as Zoophyta (animal plants) in 1742. In fact, the species name of elkhorn coral, *Acropora palmata*, comes from the palm-like shape of its branches.

Corals are vegetarians by day (relying on food produced by the symbiotic algae) but are carnivores by night. They have tentacles with small harpoon-like barbs, called nematocysts, that can eject, stab, and reel in unsuspecting prey that swim too close. Most Caribbean corals extend their tentacles only at night, but a few species, most notably pillar coral (*Dendrogyra cylindrus*), leave them out all day.

No two coral specimens are exactly alike. The myriad of shapes, both between different species and between individuals of the same species, reflect subtle differences in light, shade, and water movement in their immediate surroundings. For example, boulder corals found in deeper water are flatter, which allows them to intercept more light coming down from the water surface.

J.W. Porter - UGA

Photomicrograph of coral tentacles showing stinging nematocyst cells that appear as small white spots. When triggered, the cells release a barbed harpoon that captures prey and brings it to the polyp mouth.

Corals are among the most efficient organisms on earth

Like all plants, the symbiotic algae of corals are photosynthetic and use the energy of the sun to fix carbon dioxide from the water to produce sugars, starches, fats, and oils. The algae then "translocate" these foods directly to the animal cells. Almost nothing is lost in this transfer. Oxygen is a byproduct of photosynthesis. Most other animals on Earth are only about 10% efficient in food chain transfers. For example, when a cow eats grass, only 10% of the grass contributes to the mass of the cow.

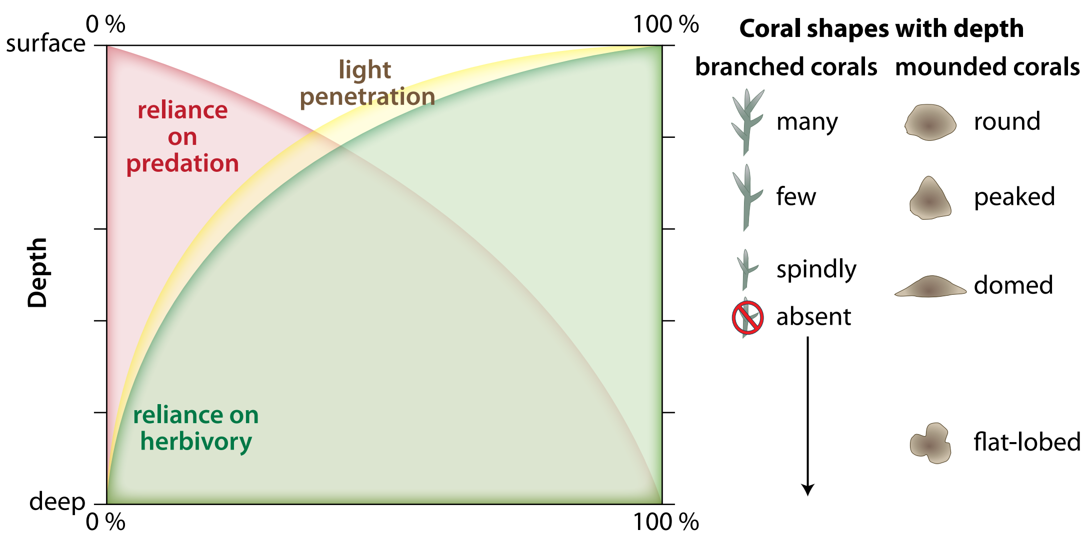
Corals are 95% efficient in transforming plant material and energy from sunlight into living coral tissue. Whenever it is sunny, corals act as plants and produce more oxygen than they consume. Corals also use energy from the sun to convert dissolved calcium in seawater into a solid calcium carbonate (i.e., limestone) coral skeleton.

Corals are very efficient at recycling materials. During the day, as algae photosynthesize, they produce oxygen and the corals consume it. In turn, corals respire carbon dioxide that the algae need for photosynthesis. However, it does not end there: the corals then excrete nitrogen and phosphorus waste, which fertilizes the plant cells.

Corals can reproduce sexually or asexually. Most release eggs and sperm into the water to produce swimming larvae called planulae. Planulae must find suitable substrate on which to settle and grow. Alternatively, corals can reproduce vegetatively when broken pieces reattach to the substrate. Vegetative reproduction is common following fragmentation of colonies after hurricanes. Regrowth by asexual reproduction produces colonies that are genetically identical to the parent stock (clones). This genetic homogeneity may put vegetative propagules at risk during disease outbreaks because they lack the genetic diversity that may favor more disease-resistant individuals.

How can the most diverse and productive of all marine communities on Earth survive and flourish in the most nutrient-poor waters on Earth?

Tropical water over coral reefs is very clear because there is so little material in it (i.e., oligotrophic). Corals flourish under these conditions because of the perfection of coral-algal symbiosis. Their reliance on solar power, energy efficiency, and material recycling has led to the long-term success and survival of coral reefs, one of the most diverse and productive environments on Earth. It is not a stretch of the imagination to suggest that corals provide a survival lesson for humankind; efficiency in the present may be a key to a sustainable future.



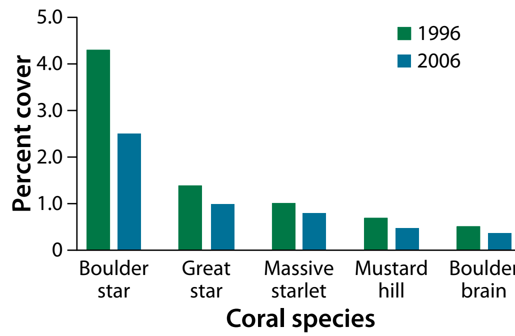
Light from the sun declines exponentially with depth on a coral reef (yellow line). As light declines with depth, reliance on photosynthesis as an energy source declines with it (green line). Corals make up for this energy loss by increasing the amount of food that they capture and eat with increasing depth (red line). As ambient light changes with depth, so do coral shapes. Branching corals usually depend more on high light intensity and disappear altogether with depth. Mounded (i.e., boulder) corals flatten with increasing depth to provide more surface area to intercept available light as the intensity of light decreases.

Thirty-two hard coral species can be found in south Florida

James W. Porter

There are 66 species of hard corals that occur in the Caribbean basin. Thirty-two of those species, including all the major reef-building (hermatypic) corals, are found in south Florida. Historically, corals were classified by 1) skeletal morphology (i.e., mounded, branching, or plating forms), 2) polyp morphology (i.e., round or elongate), and 3) polyp organization (i.e., solitary versus arranged along ridges or in valleys). Modern genetics, however, are upending this tidy classification system. For example, one Floridian species, the fused staghorn coral (*Acropora prolifera*), has recently been shown to be a genetic hybrid between elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*).

Until recently, two coral species dominated the Florida Keys Reef Tract coral reefs: elkhorn coral and boulder star coral. Elkhorn coral and closely related staghorn coral populations have declined so drastically over the past several decades that both species have been listed as Threatened Species under the United States Endangered Species Act. Hurricanes, bleaching, and disease are contributing to their loss. A major decline in the abundance of elkhorn coral in the Florida Keys occurred after two consecutive massive bleaching events in 1997 – 1998 and the species is struggling to recover. Boulder star coral (*Montastraea annularis*) is currently the most abundant coral in the Florida Keys, but its populations are also waning. From 1996 – 2006, the percent cover of *M. annularis* dropped from an average of 4.5% Keys-wide to less than 2.5%. The four other most common coral species in the Florida Keys, great star coral (*Montastraea cavernosa*), massive starlet coral (*Siderastrea siderea*), mustard hill coral (*Porites astreoides*), and boulder brain coral (*Colpophyllia natans*) have also declined in percent cover.



Mean percent coral cover loss of the five most common boulder corals in the Florida Keys National Marine Sanctuary (1996 – 2006). The most common coral, boulder star coral, experienced the greatest loss in cover.

Photographs presented on the next several pages show the diverse forms and colors of the corals found in south Florida. Some corals species have different shapes and colors than those shown here depending on the depth, available light, and other environmental conditions where they are growing. The robust ivory tree coral and the knobby star coral are commonly observed in shallow seagrass habitats because their branching morphology and superior sediment-shedding abilities allow them to flourish in soft sediments. The vast majority of the coral species pictured here can be observed on patch reefs and the outer-reef platforms of the Florida Keys Reef Tract that runs from Miami south to the Dry Tortugas. The Dry Tortugas, located 113 kilometers (70 miles) west of Key West, has the richest marine flora and fauna of the Florida Keys Reef Tract. The complex geomorphology coupled with consistently clearer water makes the Dry Tortugas a biodiversity hotspot in Florida for corals and other marine species.


J.W. Porter - UGA

Staghorn coral (*Acropora cervicornis*)


J.W. Porter - UGA

Fragile saucer coral (*Agaricia fragilis*)


J.W. Porter - UGA

Elkhorn coral (*Acropora palmata*)


J.W. Porter - UGA

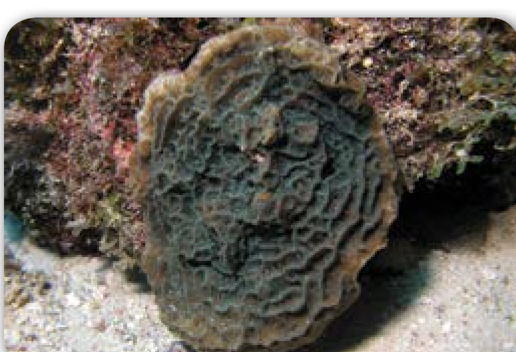
Lamarck's sheet coral (*Agaricia lamarcki*)


M. Myers - UGA

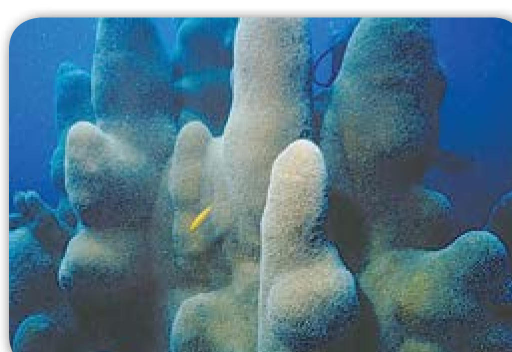
Fused staghorn coral (*Acropora prolifera*)


FWRI

Boulder brain coral (*Colpophyllia natans*)


J.W. Porter - UGA

Lettuce coral (*Agaricia agaricites*)


FWRI

Pillar coral (*Dendrogyra cylindrus*)

Elliptical star coral (*Dichocoenia stokesi*)

J.W. Porter - UGA

Smooth flower coral (*Eusmilia fastigiata*)

C. and A. Sheppard - coralpedia.bio.warwick.ac.uk

Knobby brain coral (*Diploria clivosa*)

J.W. Porter - UGA

Golf ball coral (*Favia fragum*)

FWRI

Grooved brain coral (*Diploria labyrinthiformis*)

J.W. Porter - UGA

Sunray lettuce coral (*Leptoseris cucullata*)

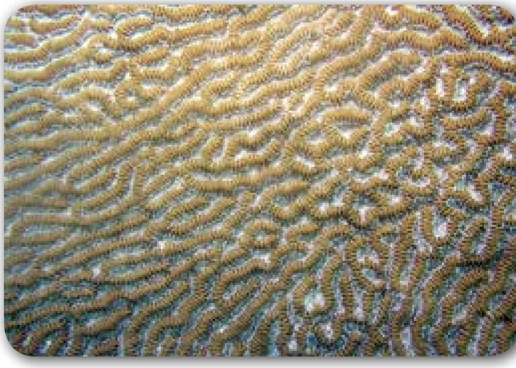
J.W. Porter - UGA

Symmetrical brain coral (*Diploria strigosa*)

J.W. Porter - UGA

Rose coral (*Manicina areolata*)

F. Charpin - reefguide.org



J.W. Porter - UGA

Maze coral (*Meandrina meandrites*)

J.W. Porter - UGA

Knobby cactus coral (*Mycetophyllia aliciae*)

J.W. Porter - UGA

Boulder star coral (*Montastraea annularis*)

J.W. Porter - UGA

Ridged cactus coral (*Mycetophyllia lamarckiana*)

F. Charpin - reefguide.org

Great star coral (*Montastraea cavernosa*)

FWRI

Spiny flower coral (*Mussa angulosa*)

C. and A. Sheppard - coralpedia.bio.warwick.ac.uk

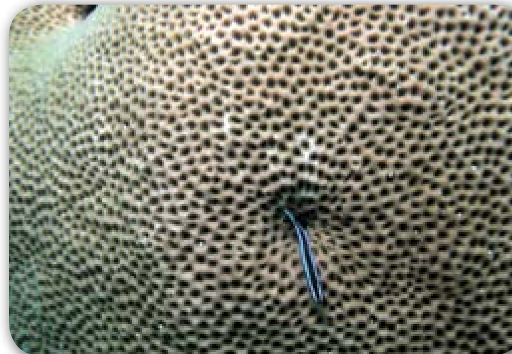
Star coral (*Montastraea faveolata*)

J. Adams - advancedaquarist.com

Robust ivory tree coral (*Oculina robusta*)

F. Charpin - reefguide.org

Mustard hill coral (*Porites astreoides*)



J.W. Porter - UGA

Massive starlet coral (*Siderastrea siderea*)

J.W. Porter - UGA

Clubbed finger coral (*Porites porites*)

F. Charpin - reefguide.org

Smooth star coral (*Solenastrea bournoni*)

F. Charpin - reefguide.org

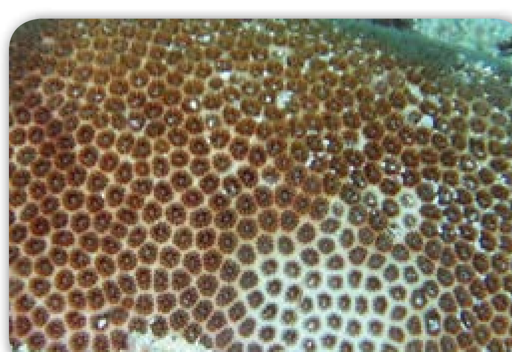
Artichoke coral (*Scolymia cubensis*)

J. Adams - advancedaquarist.com

Knobby star coral (*Solenastrea hyades*)

C. and A. Sheppard - coralpedia.bio.warwick.ac.uk

Lesser starlet coral (*Siderastrea radians*)



F. Charpin - reefguide.org

Blushing star coral *(Stephanocoenia intersepta)*

The southwest Florida coast has a unique assemblage of corals

Bryan Fluech

The diversity of stony and soft corals found off the southwest coast of Florida is very limited compared to the diversity found on the east coast of Florida. Seasonal temperature fluctuations and high turbidity are characteristics of the Gulf of Mexico that provide less than ideal conditions for most corals. Yet, several hardy species do inhabit the region.

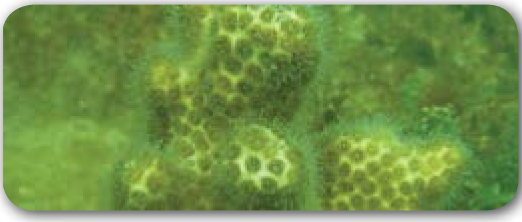
Much of the shallow continental shelf off southwest Florida consists of unconsolidated sand and shell rubble substrates overlying a limestone base rock. Isolated tracts of natural hardbottom ledges and rock outcroppings as well as artificial reefs are interspersed throughout the region and provide suitable substrate for coral colonization. Unlike many of the corals found in the Florida Keys, corals associated with southwest Florida hardbottom communities typically occur as isolated colonies and do not construct reefs. These corals and other associated biota, including macroalgae, tunicates, sponges, hydroids, and bryozoans, contribute to the productivity of southwest Florida unique hardbottom communities. They provide structure, protection, and food sources for a variety of fish assemblages and invertebrates, including recreational and commercially important species, such as red grouper (*Epinephelus morio*), gag grouper (*Mycteroperca microlepis*), and Florida stone crab (*Menippe mercenaria*).

B. Fluech - FSG

Red grouper on natural hardbottom ledge off the southwest coast of Florida.

Stony corals

Stony corals consist of polyps with multiples of six tentacles and produce an external calcium carbonate skeleton.



B. Fluech - FSG

Knobby star coral (*Solenastrea hyades*). This is one of the most common stony corals in southwest Florida. The colonies have lobed heads with irregular bulges on the surface and range from a few centimeters to 61 centimeters (2 feet) in size. Colors range from yellow-brown to cream and tan. The polyps often can be seen feeding during the day.

FWC

Hidden cup coral (*Phyllangia americana*). Hidden cup coral forms small colonies with polyps less than 2.5 cm (1 inch) wide. They settle and grow mostly on subvertical and overhanging features, thus avoiding sedimentation impacts associated with horizontal sufaces. They vary in color from yellow to reddish brown.

B. Fluech - FSG

Starlet corals (*Siderastrea* spp.). *Siderastrea siderea* and *Siderastrea radians* occur in the area as irregular rounded domes and mounds and vary in color from golden-brown to brown to gray. Colonies can range from a few centimeters to about 0.5 meters (20 in) in diameter.

B. Fluech - FSG

Robust ivory tree coral (*Oculina robusta*). This species is less common than knobby star and starlet corals and is known to prefer shallow turbid waters. Colonies form as large, "busy," tree-like structures with a thick base and can reach close to 1 meter (3 feet) in length. Color is generally yellowish brown and the colony appears "shaggy" when the polyps are fully extended.

FWC

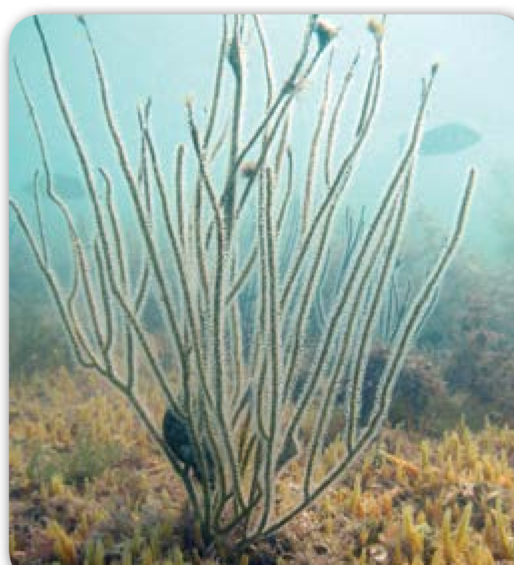
Tube coral (*Cladocora arbuscula*). Tube corals form small colonies less than 10 cm (4 in) in diameter and are typically less than 5 cm (2 in) high. They range in color from tan and golden brown to dark brown. They may be attached to rocks, especially in sedimented areas, or they may be loose and free living, commonly in rubble or seagrass.

Soft corals

Soft corals do not have hard skeletons or build reefs. Common examples include sea fans, sea whips, leather corals, and tree corals. Their body tissue is supported with small carbonate skeletal elements called sclerites that are suspended in an inorganic matrix. Sclerites give the tissues support while still allowing a lot of flexibility. The sclerites come in many shapes and sizes and are important features in the identification of soft corals.

NOAA

Regal sea fan (*Leptogorgia hebes*). Regal sea fans are thickly branched and are generally aligned in a single plane (flat). They occur in a variety of colors, including red, orange, and purple.



B. Fluech - FSG

Sea whips (*Leptogorgia virgulata*). Sea whips form long, straight, stiff, and moderately branched stalks. They occur in a range of colors, including yellow, orange, and purple.

Corals are the building blocks of reefs

Steven L. Miller, Eugene A. Shinn, and Barbara H. Lidz

Corals are colonies composed of individual polyps. Each polyp has a mouth at one end that is encircled by tentacles and a base where calcium carbonate is secreted from substances the polyp extracts from seawater. Polyps in coral colonies are interconnected and cover the limestone part of the coral (i.e., skeleton) with a thin layer of living mucus-like tissue. Under the right conditions, animals with this simple biological organization can build massive three-dimensional coral reef structures, some of which in the geologic past grew hundreds of kilometers in length and tens to hundreds of meters thick. The skeleton of each coral colony is basically rock-hard limestone and depending on the species, can range in size and shape from that of a small coin, to branching thickets the size of football fields, to massive boulder-shaped colonies the size of a school bus. Geologists often have described reefs as being similar to brick buildings, where the bricks represent coral colonies and the mortar is the cemented sediment, facilitated by calcareous algae, bryozoans, and other organisms, that holds the reef structure together.

Coral reefs are built mainly by hermatypic corals. The four common reef-building corals in south Florida are: elkhorn coral (*Acropora palmata*), boulder star coral (*Montastraea annularis*), staghorn coral (*Acropora cervicornis*), and great star coral (*Montastraea cavernosa*).

Formation of coral reefs depends on the growth of coral colonies and production of calcium carbonate by the many corals and other animals found on the reef. Factors that influence the ability of corals to grow and produce their carbonate skeletons include light, depth, temperature, and the productivity of zooxanthellae that live in the coral tissues of hermatypic corals. Light is required because the zooxanthellae, which are known to enhance calcification, are photosynthetic. Water depth is important because the quality and quantity of light change with depth. Some corals respond to decreasing light intensity at depth by growing flatter, plate-like colonies, thus presenting exposure of a greater surface area to the dim sunlight compared with their more spherical shapes when growing in shallower water. Warm temperatures are required for the formation of coral reefs, and they generally do not form where temperatures fall below 18°C (64°F) for extended periods of time. Optimal temperatures are between 26° – 28°C (79° – 82°F). Optimal salinity for reef development is between 30 – 40 parts per thousand (ppt). Under favorable conditions, boulder corals can grow up to a few centimeters (1 inch) a year, whereas branching corals can exceed 10 centimeters (4 inches) per branch over the same period.

J. Luo - UM/ RSMAS

Individual coral colonies when cemented together form coral reefs.

Physical conditions affect coral reef formation

Eugene A. Shinn

The local distribution of coral reefs is controlled by the pre-existing topography, general geography (i.e., the lay of the land), fluctuating sea level, and the kind or quality of water in which they are bathed. There are two main classes of reefs in the Florida Keys: the bank reef system and patch reef system.

Bank reefs

- Found offshore in an elongated broken arc from Miami along the Florida Keys to the Dry Tortugas.
- Located farther seaward than patch reefs.
- Significantly larger than patch reefs and have spur-and-groove formations.

Patch reefs

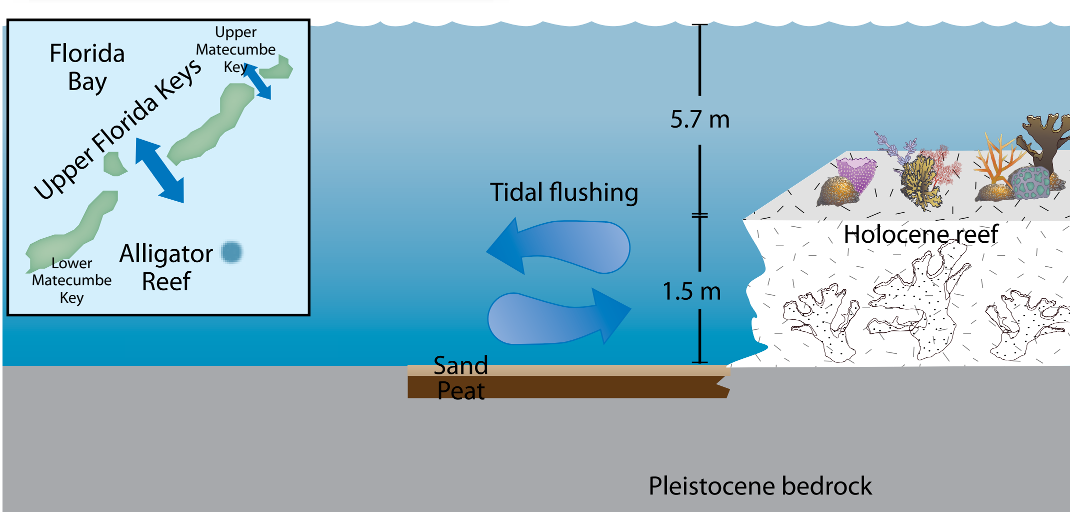
- Coral accumulations composed mainly of boulder corals.
- Singular or clustered, exist in various shapes but are generally circular to subcircular in shape.
- Commonly surrounded by bare sand, called "sand halos".

Bank reef system

Corals require a hard surface for initial settlement by their free-swimming larvae. When the sea, which is still rising today, flooded the shelf off the Florida Keys between 6000 – 7000 years ago, it submerged fossil reefs and ancient cemented beach-dune ridges. These were just the right sites for new corals to become established, and the coincident processes of rising sea level and renewed coral growth on top of elevated dune ridges and old coral skeletons continues today. But this has not happened everywhere off the Florida Keys. As sea level continues to rise, sometime in the future the present Florida Keys will be drowned once again, and more reefs will begin growing on their hard, sand-free surfaces. Again, this will not happen everywhere.

Tidal passes, the other factor

Lower Keys corals formed differently from those in the Upper and Middle Keys. This is partly due to the merging of water



Alligator Reef is limited in growth by the amount of exposed Pleistocene bedrock. The washing effect of water through the tidal pass has exposed peat and sandy sediments upon which coral reefs cannot become established.

NASA

Satellite image showing tidal passes and bank reef formations in the lee of the Florida Keys island chain.

from the Atlantic Ocean and the Gulf of Mexico and the subsequent formation of Florida Bay approximately 3000 years ago. Corals bathed in the waters from the shallow Bay became stressed by the extreme seasonal temperature fluctuations, turbidity, high salinity, and nutrients, inimical factors that limit coral growth.

So what was the result of all this change caused by a rising sea? Reefs that had begun growing off the Middle Keys and offshore from tidal passes were assaulted by outpourings of unfavorable Gulf and Bay waters. Corals either did not become established off the passes or, if present, died. The result is that there are fewer bank reef formations off the Middle Keys than elsewhere along the Florida Keys Reef Tract. The effects of rising sea level and creation of tidal passes on coral reefs are observed worldwide from the Bahamas to the Great Barrier Reef off Australia. Geologists term such a condition as reefs that were "shot in the back by their own lagoons." Any reefs that had begun growth before tidal-pass formation simply could not continue growing and are known as "give-up" reefs. All of this happened before the Keys became developed, so modern civilization cannot be blamed for poor reef growth in those areas.

The bank reef is better developed off Key Largo than in the Middle Keys because there are no natural tidal passes through Key Largo. Thus, offshore reefs there are protected from outflow of unfavorable Gulf and Bay waters. There are some areas off the oolite Keys from Big Pine Key to Key West that are somewhat protected, but there are many shallow tidal passes in the Lower Keys that funnel water toward the Atlantic. As a result, water off the Lower Keys is generally more turbid than that off the Upper Keys.

Beyond Key West and westward to the Dry Tortugas, strong north-south currents prevail. Water in that region is periodically too cold during winter months for growth of branching coral species, especially during passage of cold fronts. The temperature-sensitive branching elkhorn and staghorn corals that built reefs in the Upper Keys are for the most part absent between Key West and the Dry Tortugas. Examination of cores drilled through the reefs at Dry Tortugas shows that many species of the more temperature-resistant boulder corals, rather than those of branching corals, built the 15.2 meters (50 feet)-thick reefs at Dry Tortugas.

Patch reefs

There are thousands of patch reefs in marine waters of south Florida. Patch reefs exist primarily in wave-protected areas either in the lee of the bank reefs or in shallow, more turbid water closer to shore. A few patch reefs became established on some of the pre-existing linear reefs, but most colonized a different kind of hard surface than the linear reefs. Boulder corals recruited to the landward edges of two troughs that line the seaward side of the main, shallower, bedrock depression under Hawk Channel. There are about 3000 such patches off the Upper Keys and a few thousand closer to shore off the Lower Keys. Like the linear reefs, they are largely absent opposite the main tidal passes where they would be exposed to the full impact of Florida Bay waters.

Why do corals grow in south Florida?

William K. Fitt

Reef-building corals are restricted in their geographic distribution because the association of corals and their symbiotic algae (i.e., zooxanthellae) requires a very specific combination of temperature, salinity, and water clarity to produce the large quantities of limestone needed for coral reef formation. In light of such stringent environmental restrictions, reefs generally are confined to tropical and semitropical waters.

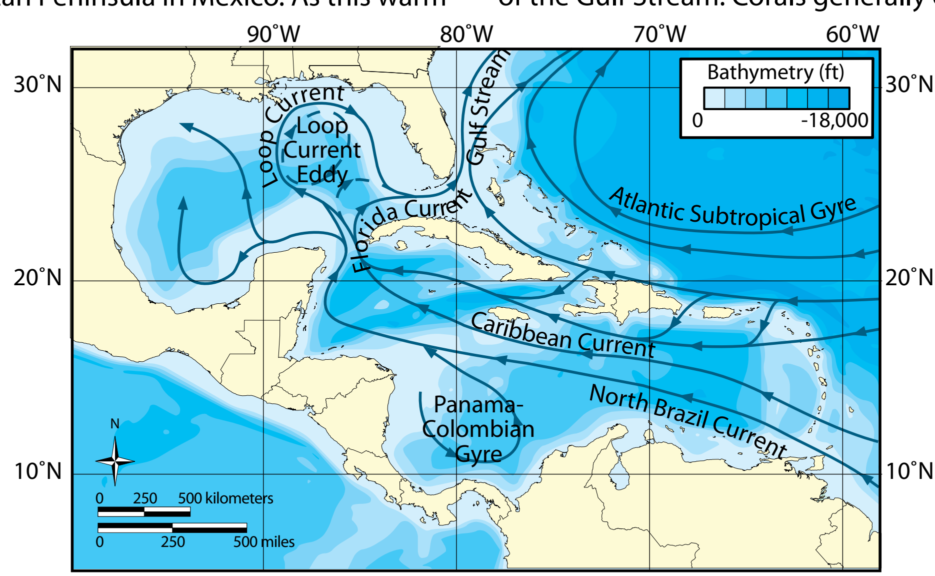
South Florida is at the northern limit of extensive reef development in North America and historically had the right mix of environmental conditions to allow hard corals to flourish and develop coral reefs.

The Gulf Stream system

Water currents circle the oceans pushed by prevailing winds. The North Equatorial Current travels west across the Atlantic Ocean. As it crosses the Equator, the waters warm up and drive the Caribbean Current that flows through the Caribbean Sea and past Central America and the Yucatán Peninsula in Mexico. As this warm water current enters the Gulf of Mexico, it forms the Loop Current in the eastern Gulf and exits the Gulf as the Florida Current. The Florida Current flows past the Dry Tortugas and up the east coast of Florida. It becomes known as the Gulf Stream as it flows past Cape Hatteras. The tropical characteristics of the Caribbean Current remain as this water mass passes around Florida and the Florida Keys. It is the influence of this current system in shallow waters that allows the temperature, salinity, and water clarity required for coral reef development in south Florida.

Temperature

The formation of highly consolidated reefs only occurs where the seawater temperature does not fall below 18°C (64°F) for extended periods of time. These conditions do not occur higher than the 30° North and 30° South latitudes. Bermuda, at 32° North latitude, is an exception to this rule because it lies directly in the path of the warm waters of the Gulf Stream. Corals generally can



The Gulf Stream current system brings warm, salty, and clear water to south Florida. This allows the development of coral reefs in areas shallow enough that adequate light reaches the bottom.

withstand temperatures as high as 30°C (86°F), depending on the species of coral, type of zooxanthellae living inside the coral tissues, and the degree on which the coral relies on the zooxanthellae to produce food (the degree of autotrophy).

The average seawater temperature in the Florida Keys is between 18°C – 20°C (64°F – 68°F), with summertime highs reaching more than 31°C (88°F). These temperatures are recorded from oceanographic recording stations located approximately 4.8 – 8.0 kilometers (3 – 5 miles) offshore and are relatively stable because of the influence of the warm Florida Current. Shallow waters experience wider variations in temperature and salinity. By comparison, temperatures recorded from Florida Bay on the west side of the Florida Keys are more correlated with air temperatures and are more variable than in deeper offshore waters.

Winter cold spells

On average, 30 – 40 cold fronts are recorded in south Florida each winter. On occasion, these cold fronts can cause water temperatures low enough to stress or kill corals. For example, during the winter of 1977, a severe cold period killed massive stands of staghorn coral (*Acropora cervicornis*) throughout the Keys and Dry Tortugas. A recent "double" cold front passed through the Florida Keys in January 2010, illustrating several mechanisms that control the growth of reef-building corals as well as the increase in environmental extremes that may be associated with climate change. The first cold front entered south Florida in early January 2010 and reduced temperatures in Hawk Channel 1.6 – 6.4 km (1– 4 mi) offshore to less than 16°C (61°F) for 1 week. This was followed immediately by a second, more severe cold front that dropped temperatures on patch reefs in Hawk Channel to less than 12°C (54°F).

Most zooxanthellate corals, octocorals, and anemones died, including 200- to 300-year-old star corals (*Montastraea* spp.). Massive starlet coral (*Siderastrea siderea*) colonies on patch reefs survived, but bleached. Some massive starlet coral colonies died when water temperatures dipped below 9°C (48°F) along the shoreline at Long Key Pass.

Cold-stressed corals, winter 2009 – 2010.

Salinity

Most corals require very salty water, ranging between 30 – 40 parts per thousand (ppt) salt. Average seawater salinity is about 36 ppt. Corals are isosmotic with salinity (i.e., have the same internal salinity as the water that surrounds them). Because of this, with few exceptions, they do not tolerate wide fluctuations in salinity. In general, the closer to the shore, the more potential there is for freshwater from rain and runoff to dilute salinity, particularly after hurricanes and tropical storms. Therefore, most reef-building corals are found at least a couple of kilometers from shore in south Florida where salinity is minimally affected by rain and freshwater runoff. Florida Bay experiences wide fluctuations in salinity, and only the most hardy, salinity-tolerant species of non-reef-building corals can survive there.

Heavy rains and coastal runoff can reduce salinities in Florida Bay to hyposalinity (i.e., low salinity) conditions. Hypersalinity (i.e., excessively high salinity) in Florida Bay is caused by droughts and/or low freshwater flows from the Everglades. Droughts in the 1950s – 1980s resulted in salinities of 50 ppt or greater at times in Florida Bay. Highly saline water is heavier than normal seawater, and when it exits the passes between the Keys, it can negatively affect corals found offshore.

Light

There is a delicate balance between the amount of light reaching corals and their health. Depth is crucial to the ability of corals to "harvest" light because light is rapidly depleted with increasing water depth. The clearer the water is (i.e., less turbid), the deeper light can penetrate. The number of species of corals on a reef declines rapidly with water depth because of decreasing light conditions. Essentially all reef-building corals are found in water less than 100 m (328 ft) deep because of their reliance on the light requirement of their zooxanthellae for nutrition.

If corals receive too little light, the zooxanthellae in corals cannot photosynthesize efficiently; if they receive too much light, the zooxanthellae may be expelled from the coral tissue and the coral may bleach. Shading from turbidity, including phytoplankton, may be one reason that corals on shallow patch reefs in Hawk Channel appear to be "healthier" than corals growing on the fore reef in the Keys. High incidence of ultraviolet light can trigger coral bleaching; the turbidity in Hawk Channel reduces the amount of ultraviolet light reaching the corals.

Nutrients

Water clarity is affected by nutrients. More nutrients result in more phytoplankton and less light penetration in the water column. Generally, water over coral reefs is very low in dissolved nitrogen and phosphorus nutrients. Nutrient pollution from nearfield and farfield sources has the potential to adversely affect coral reefs. Potential sources of nutrient pollution in south Florida are from land and nutrients delivered from the Southwest Florida Shelf and the Gulf Stream system. Also, occasional cold water upwelling events deliver nutrients to the fore reef.

Calcium carbonate concentration

Reef waters are typically saturated with calcium carbonate. Zooxanthellae in corals photosynthesize (fix carbon) from bicarbonate ions dissolved in seawater. Carbonate chemistry in seawater is relatively complex. The availability of the required form of dissolved carbon is primarily controlled by the temperature and pH (i.e., acidity) of the seawater. If seawater pH decreases (i.e., ocean acidification), as is predicted because of an increase in CO_2 in the atmosphere, it could result in a change in availability of carbon to the zooxanthellae and a change in calcification rates of corals, calcareous algae, and organisms that produce calcium carbonate shells (e.g., sea urchins, benthic and planktonic foraminifera, snails, clams).

Sediments

High concentrations of sediments in the water column can smother coral colonies, clog the mouths of coral polyps, and impair feeding. Suspended sediments can also decrease the depth that light can penetrate into the water column and limit coral growth and survival. Suspended sediments are generally higher on the Gulf side of the Keys compared to the Atlantic side. Reef development on the Atlantic side of the Keys has historically been reduced opposite large tidal passes between the Florida Keys because of the sediment-laden and seasonally cold Gulf waters from the Southwest Florida Shelf and from Florida Bay that are inimical to coral growth and reef development.

Conclusion

Coral reefs can be stressed by local, regional, and global stressors that can be caused by humans or natural events. South Florida coral reefs are degrading, reflecting a worldwide trend in coral decline. Reasons for the decline in coral cover in south Florida are attributed to multiple stressors, including nutrient pollution from nearfield and farfield sources, variations in temperature, salinity, sediments, light availability, and carbonate chemistry of seawater.

Stony corals exhibit several reproductive strategies

Steven L. Miller, William F. Precht, and Struan R. Smith

Some corals reproduce asexually when pieces break (i.e., fragment), reattach to the bottom, and grow into new colonies. Fragmented corals are genetically identical to their parent colony. Most corals can reproduce sexually, and some species are hermaphroditic, meaning that both sexes are found in the same individual.

There are two main forms of sexual reproduction in corals. Some are broadcast spawners and release eggs and sperm into the water where fertilization occurs. Fertilization results in a larva (i.e., planula) that is transported by currents for days or longer before settling to the bottom, attaching to a suitable substrate, and growing into a polyp that eventually becomes a coral colony. Other coral species are brooding corals where fertilization is internal. Larvae are released from brooding corals into the water, and they settle and attach to the bottom within hours after being released.

New corals have to establish themselves (i.e., coral recruitment) in order for degraded reefs to recover and for healthy coral populations to sustain themselves. Lack of sufficient numbers of adults to produce a suitable number of larvae (i.e., sexual) or coral fragments (i.e., asexual) may limit recruitment of new colonies.

P. Gillette - UM/RSMAS

A broadcast spawning coral (*Montastraea*) in the Florida Keys releasing gamete bundles (pink spheres) during a spawning event. Broadcast spawners release eggs and sperm into the water column where fertilization takes place. Fertilized eggs develop into larvae (i.e., planulae) that are transported by ocean currents before settling on suitable bottom habitat and forming a coral colony.

Coral larval attachment may be limited by the presence of benthic algae or sediments. In addition, micropredators, such as brittle stars, may consume newly settled larvae. Recruitment can also be influenced by geography. For example, larval settlement in the Middle Keys may be affected by discharges from Florida Bay, whereas the coastal waters of the Upper Keys are protected from those discharges.

Massive starlet coral (*Siderastrea siderea*), a broadcast spawner, has the highest number of new recruits at most sampling stations in the Florida Keys. However, in general, smaller brooding corals, such as species of *Porites* and *Agaricia*, are more successful with recruitment and have a higher density than broadcast spawners at most sampling sites. Brooding species reproduce throughout the year, grow fast, and do not live as long as more massive broadcast spawners. For these reasons, they are called "weedy" coral species. The massive species, such as the star corals (*Montastraea* spp.) and brain corals (*Diploria* spp.) are broadcast spawners that reproduce only once or twice a year. They are long-lived on the order of decades or longer, and they only need to reproduce successfully once during their long lifetimes to successfully replace themselves.

Recruitment of corals in the Florida Keys is similar to that found in the Caribbean in terms of absolute numbers and patterns among species groups. Recruitment of many broadcast spawning coral species has always been an infrequent event, even when the species were very abundant on Caribbean and Atlantic reefs. Thus, low recruitment of these long-lived species may be sufficient to maintain current population numbers but seriously inhibits the recovery of populations devastated by diseases and bleaching events.

Geologic tools are used to decipher the history of reef formation

Steven L. Miller, Eugene A. Shinn, and Barbara H. Lidz

Our knowledge of how and when reefs accrete is based on data obtained with several different technologies. A complete picture emerges when data sets are combined.

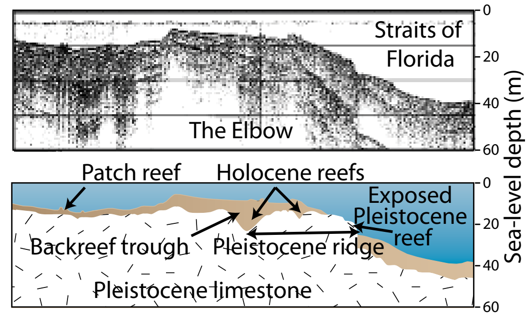
Cores

Cylindrical cores can be cut out of a coral reef with a lightweight diver-operated drilling system. The hard cores are sliced in the laboratory with a rock saw. The core slices provide a cross section of the reef that represents growth over long periods of time. Core material can be dated, and the growth of individual corals and of the reef as a whole can be measured. Rates vary but are generally in the range of millimeters to centimeters per year for healthy reefs. Cores from reef interiors show that reefs consist of everything from sections dominated by species of stony corals growing on top of one another to a mix of coral fragments, carbonate shells, debris, sediment, and even open spaces.

Scientists use a pneumatic coring device to obtain coral cores.

Seismic profiling

Graphic cross sections of reefs can be viewed using seismic profiling instruments, which are essentially high-powered fish finders that penetrate the seafloor with sound waves. The profiles comprise characteristic lines produced when sound is reflected back from the



Top: seismic profile of The Elbow reef (Upper Keys). Bottom: interpreted line drawing of the above seismic profile.

rock surfaces below. The lines mimic those surfaces. These profiles help geologists to evaluate reef formation, structure, thickness, and geometry.

Exposed fossil reefs

Actual cross sections of coral limestone reefs can be viewed in areas where reefs are exposed naturally or where they have been exposed by human activities, such as canal excavation and mining. The Windley Key Fossil Reef Geological State Park in the Middle Florida Keys is a limestone quarry excavated in an emergent coral reef. The quarry once supplied building stone for many public buildings in Miami. The emergent reef, which grew during a time of higher sea level about 125,000 years ago, now forms all islands of the Upper and Middle Keys.

The history of reef formation is exposed in Key Largo Limestone at Windley Key Fossil Reef Geological State Park.

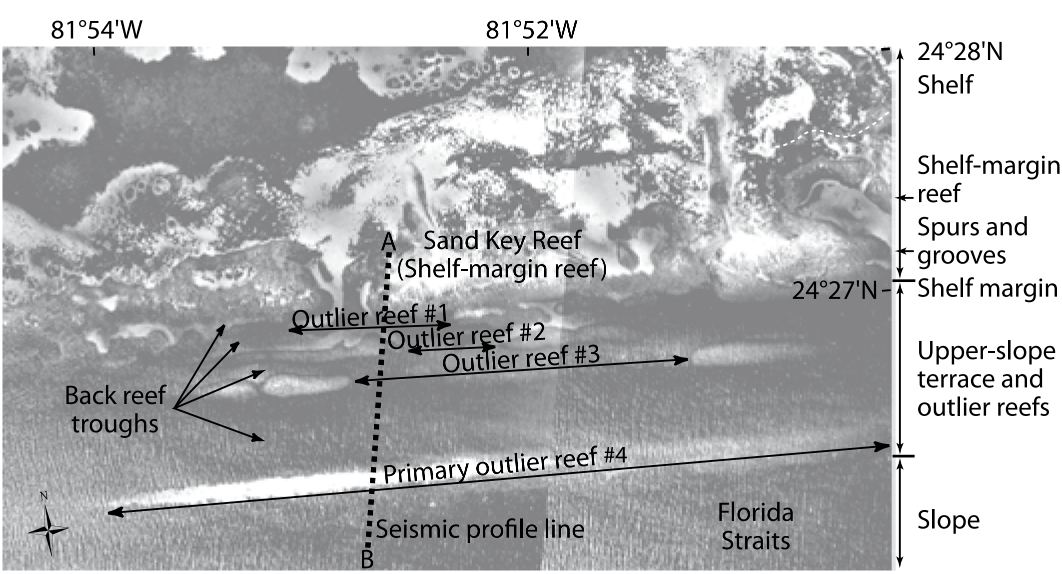
Outlier reefs are found off the Florida Keys

Barbara H. Lidz

Research into how, where, when, and why modern coral reefs grow led to an investigation of a series of immense linear rock ridges that are found beyond the present shelf margin (bank) reef off the Lower Keys. Aerial photomosaics show that the ridges are discontinuous and parallel to the shelf margin. Seismic profiles indicate that they developed on a 40 meter (130 feet)-deep terrace seaward of the shelf edge. The outermost ridge is the largest (primary outlier reef) and is nearly 30 m (100 ft) high, 1.6 km (1 mi) wide, and 56 kilometers (35 miles) long. Navigation charts of the area depict the ridges. Seismic profiles along the same terrace off Key Largo (Upper Keys) show four similar linear structures, but they are much smaller, only a meter or so high, narrower, and are buried by sediments.

Scientists drilled a core in the outermost ridge off the Lower Keys and found that the ridge consists of corals. The other parallel formations are also reefs. By using radiometric dating methods, researchers determined that the fossil reefs were alive about 80,000 years ago during a global high stand of sea level, one of several that occurred in a period of geologic time called the Pleistocene. These reefs are named outlier reefs because they are seaward of the shelf-margin reef that harbors modern coral and hardbottom communities.

The terrace upon which the outlier reefs grew represents a previous shoreline that may be as recent as 190,000 years old. Its 3.2 km (2 mi) width indicates that the shoreline existed for a long time and that sea level may have remained near that position for thousands of years. While exposed, it is likely that winds formed sand dunes along the shoreline and that sand grains in the dunes became cemented with time. As a rising sea surface flooded the terrace, the hardened dunes were also submerged and corals colonized their surfaces. For unknown



Photograph courtesy of J. Pitts - FDOT

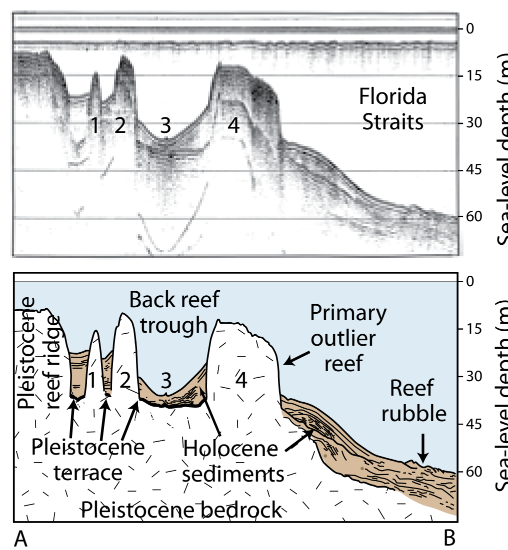
Aerial photo of the region seaward of Sand Key Reef shows the four discontinuous tracts of outlier reefs seaward of the shelf-margin reef. The seawardmost outlier reef (#4) is the largest. The seismic profile was taken along transect A – B.

reasons, corals did not survive on the northern dune ridges (Upper Keys) but they thrived off Key West, and organisms typically associated with a healthy coral reef ecosystem were probably abundant. As the sea continued rising, those corals flourished, keeping up with the rise, and over thousands of years, they constructed the huge outlier reefs.

All scientific information available indicates that during the period of outlier-reef formation, sea level remained below elevation of the Florida shelf. Florida Bay did not exist, and the growing outliers were thus sheltered from shallow coastal and Bay waters that would have been deleterious to their survival. A broad continuous spit of land that included all of what are now Florida Bay, the Florida Keys and shallow shelf, and the Marquesas-Quicksands Ridge, jutted into the Gulf of Mexico and protected the growing reefs from cold Gulf waters as well. Then, around 77,800 years ago, a time that corresponds to the age of the youngest cored and dated Pleistocene coral, sea level fell well below the Florida shelf and remained below until about 8000 years ago. During those thousands of years, corals remained exposed to air and could not grow. When sea level rose once again, it flooded the outlier reefs and shelf. Corals again grew briefly on the Lower Keys outlier reefs, from about 8900 – 6900 years ago, but then coral growth stopped.

What caused the abrupt demise of the outlier-reef builders shortly after 6900 years ago is not known. One theory is that as water became deeper across the shelf, it eventually linked turbid, cold Gulf waters with the clear, warm Atlantic Ocean waters needed by the corals. This exposure to cold temperatures weakened the corals, and reef building ceased.

Today, the surface of the largest outlier reef (primary outlier reef) in the Lower Keys lies about 9 m (30 ft) below sea level and harbors only a very few widely scattered heads of live coral. Storm waves remove and push loose coral and sand from the reef crests into the deep troughs behind the coral-rock ridges. Eventually, given enough time, the broad troughs will fill, as is known to have occurred in the Upper Keys where Holocene sands pushed by onshore winds and waves have filled sections of the much shallower 80,000-year-old back reef trough behind the shelf-margin reef. The infilling was rapid, relative to geologic time, having taken place within the most recent 8000 years of shelf flooding. Given their greater breadth and depth and the alongshore direction of winds and waves in the Lower Keys, a considerably longer amount of geologic time will be needed to fill the outlier reef troughs.



From Lidz et al. (1991)

Seismic profiles (A – B) present a sound wave "picture" through rock and sediment. Sound waves pass through the ground and echo or reflect back different types of sediment and rock surfaces. A machine records the echoes and draws a picture of the reflections. Top: a seismic profile across the shelf margin and outlier reefs seaward of Sand Key Reef, southwest of Key West, Florida. Currents flowing essentially westward, toward the reader and parallel to the rock ridges, prevent the troughs between the margin and outlier reefs from rapidly filling with layers of sand and coral debris. The troughs are known as "back reef troughs." Note the reflection (heavy line) that marks the hard rock surface of the old (Pleistocene) terrace floor. The primary outlier reef (#4) grew at the seaward edge of the terrace. Bottom: interpreted line drawing of the seismic profile shows an outline of the cross section of the four parallel tracts of outlier reefs. The tracts are discontinuous. The seismic profile just clipped the end of a reef in tract #3. Note that the terrace cannot be traced below the outlier reefs because coral reefs and coral debris characteristically block transmission of sound waves. Depth below sea level is in meters.

Discharges from Florida Bay influence growth of corals

Clayton B. Cook, Erich M. Mueller, Eric R. Annis, and M. Drew Ferrier

There are many differences in water quality between Florida Bay and the Florida Keys Reef Tract. The shallow Bay has greater temperature extremes, more variation in salinity, and finer sediments than the bank reefs. Bay waters also have elevated nutrients (i.e., nitrogen and phosphorus), and are much more turbid than water at the Reef Tract. These differences are reflected in the corals found in the two environments. Depending on location, the Florida Keys Reef Tract has 32 (Biscayne National Park) – 47 (Dry Tortugas) species of hard corals that form the structural framework of the reef system. In contrast, only four species of stony coral (rose coral [*Manicina areolata*], finger coral [*Porites porites*], lesser starlet coral [*Siderastrea radians*], smooth star coral [*Solenastrea bournoni*]) are commonly found in Florida Bay. These are hardy corals that can withstand the environmental challenges presented by Florida Bay waters.

Google Earth

Turbid (lighter-colored) waters flow out of Florida Bay through Channel 5 and toward the reef tract. Inshore is the location of the coral transplantation study site in the tidal flow from Channel 5. Offshore is the location of the transplantation study site on the eastern edge of the bank reef.

Water is exchanged between Florida Bay and the Atlantic Ocean through tidal passes between the Keys, flowing from the Bay to the ocean during ebbing tides and reversing during flood tides. However, there is an overall net flow from Florida Bay to the Atlantic. An alongshore counter current flowing to the southwest in Hawk

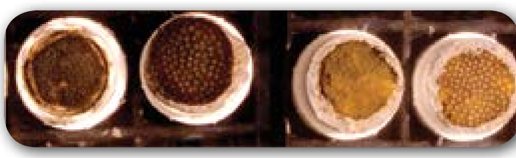
E.M. Mueller - MML

Stainless steel coral maintenance structure used to deploy coral cores at the two sites. Each coral core was about 51 millimeters (2 inches) in diameter and was mounted in a PVC collar screwed into the structure.

Channel intercepts some of this flow. Reef growth is greatest in areas that are not exposed to direct flow from Florida Bay.

An experiment was performed in 1996 – 1997 to assess how Florida Bay waters actually affect reef corals. Cores of the same size were cut from large colonies of the large star coral (*Montastraea faveolata*) and were transplanted to two sites south of Long Key. Both sites were at equivalent depths (3.6 – 4.6 meters [12 – 15 feet]). The inshore site was located in the tidal flow from Channel 5, whereas the offshore site was located across Hawk Channel on the eastern edge of Tennessee Reef. Transplanted corals were sampled and structures were cleaned every 3 months for 15 months.

The corals from the inshore site were typically darker in coloration than those at the offshore site at every sampling period because of an increased amount of chlorophyll. Reef-building corals contain symbiotic algae (i.e., zooxanthellae) in their tissues. These algae are responsible both for the productivity of reef corals and for the accelerated rate of calcium carbonate deposition (i.e., coral skeleton formation) that results in growth and formation of coral reefs. Inshore corals had increased chlorophyll content of these algae due to the elevated turbidity (i.e., decreased light transmission) of the Florida Bay water. It is common to see an elevated chlorophyll content in shaded corals; the algae synthesize more photosynthetic pigments to trap more light under reduced illumination, and appear darker in color.



C.B. Cook - HBOI

Coral cores collected 9 months after deployment. The difference in pigmentation between corals placed inshore (two darker corals on left) and offshore (two lighter corals on right) is due to increased photosynthetic pigments in corals growing in inshore turbid (shaded) water.

At the beginning of the experiment, each coral core had the same area of living coral tissue. After 15 months, the corals growing offshore appeared healthy, whereas coral cores growing at the inshore site were smaller, and in some, part of the core was missing. Inshore corals had less live tissue and a smaller number of coral polyps than offshore corals.

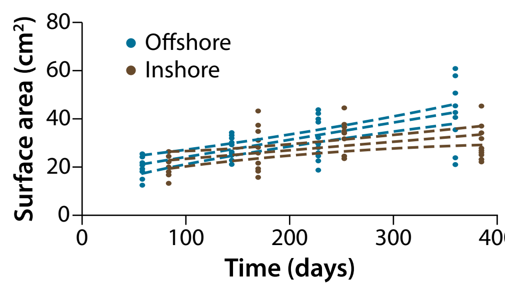
The loss of skeleton in some of the inshore corals may be related to the less dense skeletons that these corals

C.B. Cook - HBOI

Coral cores collected 15 months after deployment. Left: inshore coral. Right: offshore coral. Some corals growing inshore had areas devoid of coral tissue and places where the skeleton was broken.

produced. The linear extension (increase in diameter) was similar between the two study sites, but the actual amount of calcium carbonate that each unit deposited during the experiment was always greater at the offshore reef site. This indicates that the inshore corals were making less dense skeletons that were potentially weaker and more prone to the activities of boring organisms, such as sponges and bivalves, that bio-erode coral skeletons.

One model of coral growth states that linear extension is not light limited, but bulk calcification is light limited. It appears that turbidity results in reduced coral calcification by reducing the amount of light available to the zooxanthellae for photosynthesis. The increased chlorophyll content of the algae seems to be insufficient to compensate for this.



After 15 months, the coral transplants growing offshore (blue) had significantly higher surface areas than inshore transplants (brown).

The most likely explanation for the growth patterns observed is that light limitation of bulk $CaCO_3$ deposition was greater at the inshore site. Similar patterns of coral growth, resulting from turbid water, have been observed in Mexico and on the Great Barrier Reef in Australia.

This research demonstrates that turbidity is one of the major inimical factors of Florida Bay waters that inhibit the growth of reef corals and, thus, coral reefs, but it certainly is not the only one. High turbidity operates in concert with the other factors (e.g., nutrient loading, temperature and salinity fluctuations) in reducing the ability of most reef corals to be competitive in this environment.

Long-term monitoring documents the decline of corals in the Florida Keys and Dry Tortugas

Rob Ruzicka

The Florida Keys Coral Reef Evaluation and Monitoring Project (CREMP) was initiated to monitor the status and trends of coral reef resources in the Florida Keys National Marine Sanctuary (FKNMS) and Dry Tortugas. The program is a cooperative effort between the United States Environmental Protection Agency, the National Oceanic and Atmospheric Administration, and the Florida Fish and Wildlife Conservation Commission. CREMP is one component of the FKNMS Water Quality Protection Program, which includes monitoring projects for seagrasses, coral reefs, and water quality. CREMP began annual sampling in 1996 in the FKNMS, and in 1999, additional sites were installed and sampled in the Dry Tortugas.

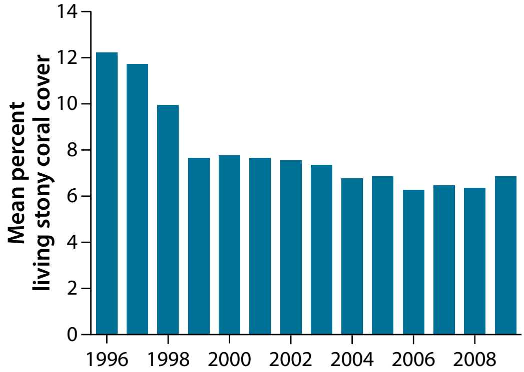
R. Ruzicka - FWRI

The Coral Reef Evaluation and Monitoring Project monitors 34 sites in the FKNMS and three sites in the Dry Tortugas annually.

Each sampling site consists of two to four monitoring stations delineated by permanent markers. Stations are approximately 2 meters (6.5 feet) wide by 22 m (72 ft) long and generally run perpendicular to the reef crest. Within each station, CREMP records stony coral species richness, coral disease presence and absence, and the number of *Diadema* sea urchins and uses three video transects to measure the spatial coverage of stony corals, octocorals, macroalgae, sponges, and other coral reef flora and fauna. Results are analyzed Sanctuary-wide and by region for the Upper Keys, Middle Keys, Lower Keys, and Dry Tortugas. Currently, CREMP monitors 109 stations at 34 sites in the Florida Keys and three sites in the Dry Tortugas.

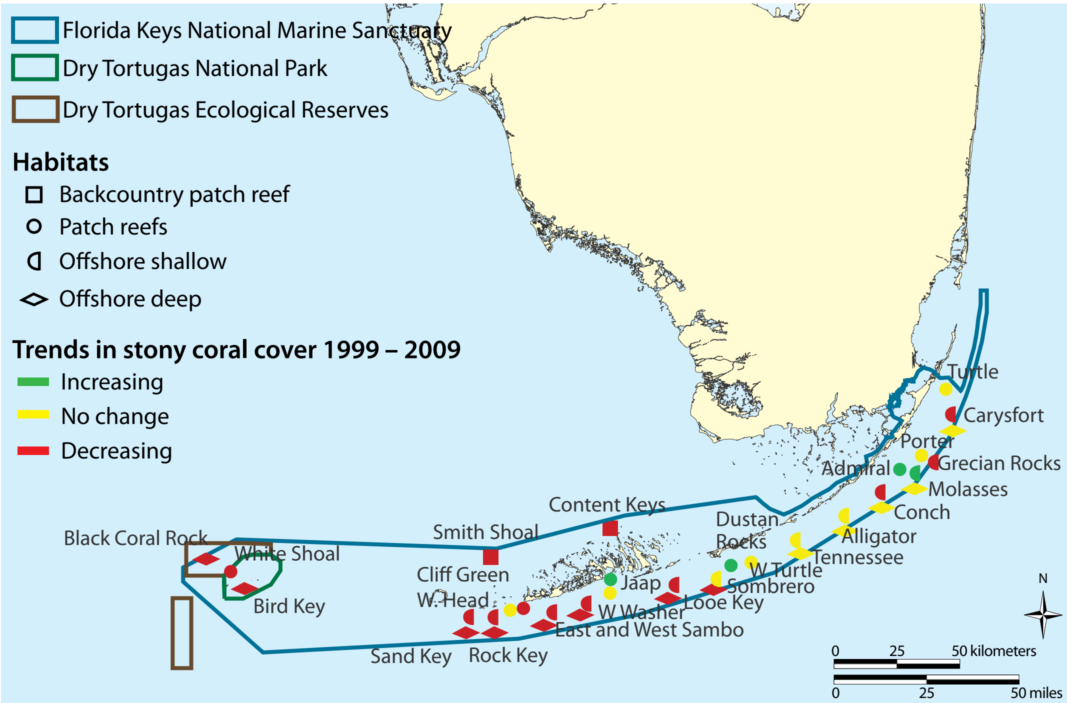
Stony coral cover

Over the duration of the project (1996 – 2009), living coral cover declined from 12.7% to 7.3% Sanctuary-wide. Coral cover reached its lowest level (6.4%) in 2006. Several factors have contributed to the major losses in coral cover.



Mean percent living stony coral cover decreased santuary-wide from 12.7% in 1996 to 7.3% in 2009. Coral cover reached its lowest level (6.4%) in 2006. A large decline in coral cover occurred in 1998 and 1999 following two consecutive years of extensive coral bleaching. There was a small increase in stony coral cover between 2008 – 2009.

Successive and severe declines in coral cover took place in 1998 and 1999 due to a prolonged El Niño weather pattern that caused extensive coral bleaching and mortality throughout the Caribbean and Western Atlantic. Also, Hurricane Georges struck the Keys in September of 1998 and caused widespread coral damage. The decline in stony coral cover between 2005 – 2006 can be attributed to the 2005 Atlantic hurricane season, the most active hurricane season on record, in which several storms passed through or were



Location of CREMP sampling locations throughout the Florida Keys and Dry Tortugas. Different colors show the proportional changes in stony coral cover over the past 10 years of monitoring (1999 – 2009). The different symbols indicate the type of coral reef habitat monitored. Significant declines in coral cover were observed in offshore shallow and deep reef sites in the Lower Keys and Dry Tortugas and Backcountry (red). No significant change in coral coverage was observed in most Atlantic patch reefs (yellow circles). Three patch reef sites, Jaap Reef, Dustan Rocks, and Admiral Reef (green circles), and one offshore shallow reef site, Molasses Reef (green half circle), had a significant increase in coral cover.

adjacent to the Keys. Although hurricanes and coral bleaching events have had a major impact on corals in the Florida Keys and Dry Tortugas, other acute and chronic stressors, such as coral diseases, periodic algal blooms, and decreasing water quality may also contribute to decreased coral cover.

Over the past 10 years of monitoring, coral cover decreased at 20 of 37 (54%) sites, remained similar at 13 (35%) sites, and increased at 4 of 37 (11%) sites. There were significant differences in coral cover between regions and type of reef habitat. Two thirds of all deep and shallow fore reef sites have declined in coral cover. In contrast, 80% of patch reef sites had no change or an increase in coral cover. Regional differences in declines were stark, especially in the Dry Tortugas and the Lower Keys where 16 of 19 sites (84% combined for both regions) showed a declining trend in coral cover, whereas most Middle and Upper Keys sites had no significant change in coral cover over the past 10 years.

The five coral species with the highest mean percent cover in 2009 were boulder star coral (*Montastraea annularis*), great star coral (*Montastraea cavernosa*), massive starlet coral (*Siderastrea siderea*), mustard hill coral (*Porites astreoides*), and boulder brain coral (*Colpophyllia natans*). Since 1996, each of these species has had a percent cover greater than 0.5%. In many cases, the overall decline of stony coral cover throughout the Florida Keys and Dry Tortugas is largely due to the decreased cover of boulder star coral. Coral cover for the other species aforementioned has been steadily declining as well, except for massive starlet coral, which has increased slightly in percent cover.

Cover of elkhorn coral, now listed as threatened under the U.S. Endangered Species Act, contributed greater than 1% coral cover during the first 2 years of the project but declined significantly when it was decimated by disease in 1999. In 2 years, elkhorn coral cover was reduced from greater than 1% to less than 0.2% and has not recovered.

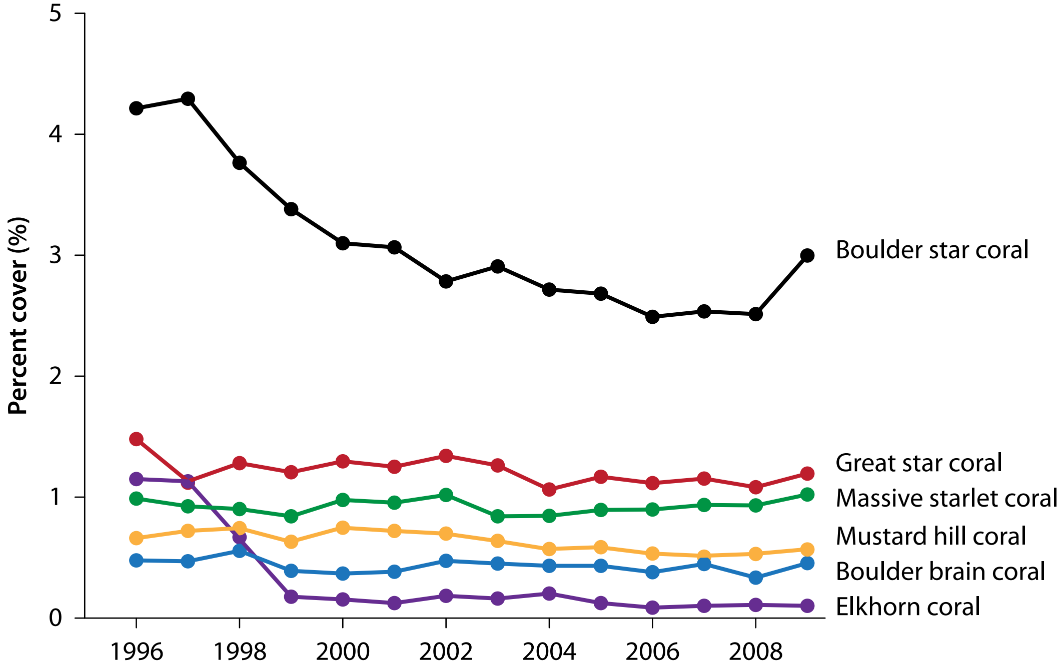
Species richness

Species richness is the number of species found at a location. The maximum number of hard coral species found in a single year was 46 in 1999 when all sites in the Florida Keys and Dry Tortugas were combined. Seventy-six percent of all monitoring stations showed a decrease in number of species over the sampling period. On average, the number of species occurring at each station declined by three species during the past 14 years.

F. Charpin - reefguide.org

Coral cover for massive starlet coral has been increasing slightly since 2003.

When presence and absence of species are compared for all stations sampled during the 14-year sampling period, 29 species are present at fewer stations than when they were previously observed. Only 9 coral species are now found at more stations than were observed in 1996. The occurrence of two species has not changed since 1996.

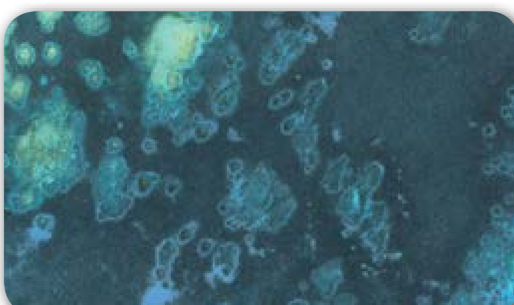


Changes in mean percent stony coral cover for the six most spatially dominant species from all sites. Boulder star coral (black) declined the most over the 14-year sampling period. Note that coverage of elkhorn coral (purple) declined precipitously from 1997 – 1998 and has not recovered.

Patch reefs are healthy reef habitats

Diego Lirman

Patch reefs are found in shallow water (1.8 – 9 meters [6 – 30 feet] deep) between the shoreline and the outer-bank reefs. They are a unique and defining characteristic of the coral reef ecosystem of southeast Florida. More than 6000 individual or aggregated patch reefs have been mapped from Miami to the Dry Tortugas. Patch reefs usually are circular or elliptical in shape and commonly are surrounded by sand or seagrass. They range in size from a few meters up to about 730 m (2395 ft) in diameter and can have 1 – 3 m (3 – 10 ft) of vertical relief.


NPS

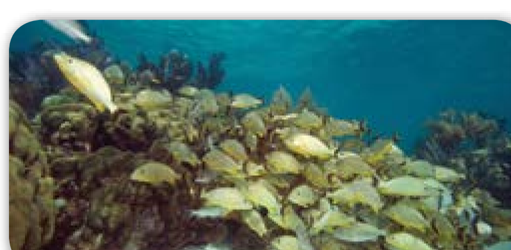
Aerial photograph of a portion of the northern Florida Keys Reef Tract showing a large number of lagoonal patch reefs.

The main corals found on patch reefs include star corals (*Montastraea* spp.), massive starlet coral (*Siderastrea siderea*), and brain corals (*Diploria* spp.). Patch reefs, especially those found fewer than 5 kilometers (3 miles) from shore, are among the healthiest reef communities of the Florida Keys Reef Tract, based on their high percentage of live coral cover (maximum coral cover is greater than 50%; mean coral cover is 17%). Also, the coral colonies found at patch reefs have little partial mortality (i.e., most of the coral colony is alive), and there is a high abundance of reef fishes.

A prominent feature of patch reef habitats is an abundance of large colonies of star corals (*Montastraea* spp.) that often exceed 1.8 m (6 ft) in diameter. Large, healthy star corals are increasingly rare in other reef habitats of the Florida Keys. Aggregations of these colonies often are described as clusters and provide essential habitat for many reef fishes and hard substrate for other benthic organisms. In addition, the reproduction by these large, old-growth corals can provide larvae to help to replenish depleted offshore reef habitats.

Many animals are residents of patch reefs as adults, such as spiny lobster and red grouper. Patch reefs also provide important habitat "pit stops" in the life history migration of commercially important fish and invertebrate species because of their location between bank reefs and the coastal wetlands and seagrass beds. Many species that spawn offshore have larvae that migrate into nursery habitats in Biscayne Bay and Florida Bay and can be found at patch reefs during their migration and development.

Many of the larger patch reefs in the Florida Keys National Marine Sanctuary are protected as Special Protected Areas (SPAs), including Hens and Chickens, Cheeca Rocks, and Newfound Harbor reefs. In SPAs, only nonconsumptive recreational activities are allowed, such as snorkeling, SCUBA diving, and glass-bottom boat rides. The major objective of the designation of reef areas as SPAs was to resolve conflicts between consumptive and nonconsumptive users.


E. D'Alessandro - UM/RSMAS

Schools of grunts and snappers are common sights on patch reefs in southeast Florida.

Coral cover in Dry Tortugas National Park has substantially decreased from historic amounts

Douglas Morrison

Coral reefs are one of the most important natural resources in Dry Tortugas National Park, and branching (acroporid) corals are a main reef builder. There are three species of branching corals in the Park: staghorn (*Acropora cervicornis*); elkhorn (*Acropora palmata*); and a hybrid species of staghorn and elkhorn coral, fused staghorn coral (*Acropora prolifera*). Reefs in the Dry Tortugas have been monitored since 1881, and staghorn coral has historically accounted for more than half of the coral reef coverage. In 1881, Alexander Agassiz mapped 461 hectares (1140 acres) of branching coral reefs, mostly staghorn coral. In 1976, the area covered by branching corals was found to be 478 ha (1181 ac). By 2009, however, there was only 0.5 ha (less than 2 ac) of known acroporid reefs in the Park, a 99% loss.

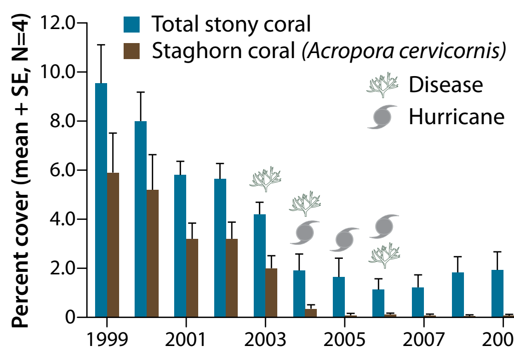
D. Morrison - NPS

Healthy (left) and diseased (right) fused staghorn coral (*Acropora prolifera*). Disease and hurricanes have resulted in recent losses of corals in Dry Tortugas National Park.

Annual detailed benthic surveys in Dry Tortugas National Park were initiated in 1999. Results show a marked decline in total percent cover of coral from 1999 – 2006, and an increase in total coral cover from 2007 – 2009. However, there has been a 99% decrease in the spatial extent of branching corals in the Dry Tortugas since 1999, with little recovery.

Causes for the decline

A cold-water event in 1977 caused nearly 90% mortality of staghorn coral in Dry Tortugas National Park. However, that species started recovering in the 1980s, but disease outbreaks caused a substantial loss of all branching corals during the 1990s and early 2000s. For example, a patch of fused staghorn coral near Garden Key experienced a 90% mass mortality in 2003 because of disease.



Percent stony coral cover at White Shoal, Dry Tortugas National Park. Total coral cover decreased 83% from 1999 to 2009 with some recovery since 2007. Staghorn coral decreased 98% over the same period and has shown no recovery.

Branching corals are very susceptible to physical damage due to hurricanes and tropical storms. Five hurricanes passed over the Dry Tortugas in 2004 – 2005, an unprecedented event, and caused additional losses of branching coral coverage. However, by 2009, live coverage of total, fused staghorn and elkhorn corals were not statistically different from 2004, suggesting recovery from the 2005 hurricanes. In contrast, staghorn coral decreased 98% at two monitoring sites from 1999 – 2009, with no recovery. The 2010, the cold-water event was found to have no effects on acroporid corals in Dry Tortugas National Park.

The National Park Service has partnered with The Nature Conservancy to grow and transplant corals to attempt to restore acroporid coral reefs in the Park.

Foraminifera are useful indicators of environmental conditions of coral reefs

Pamela Hallock

Foraminifera (i.e., forams) are a very diverse group of single-celled organisms that occur in most marine environments. They are characterized by a protective shell, usually of calcium carbonate, that can have single or multiple chambers. Multiple chambers are interconnected by openings called foramen from which they get their name. Approximately 5000 species of forams exist today. They are well preserved in the fossil record, and more than 50,000 fossil species of forams have been described. They are very abundant organisms and form carbonate sediments, "oozes" on the ocean floor, and sedimentary rocks. The most famous foram accumulations are the limestones of Egypt from which the pyramids were built.

Some forams are planktonic, but most live on the seafloor; in the bottom; or attached to a substrate, such as seagrass leaves, as epiphytes. A wide range of environmental factors influences where individual species can live. They have a relatively short life span, very specific ecological requirements, and a rapid response to environmental changes. Thus, the presence or absence of particular species or assemblages of species has been found to be very useful indicators of present or past environmental conditions.

P. Hallock - USF

Photomicrograph of three species of multichambered marine foraminifera with symbiotic algae. The largest is about 2 mm (0.8 in) in size. Such forams bleach when environmental conditions become unfavorable. Monitoring the species assemblages of forams provides a simple, noninvasive indicator of water quality.

They are also useful tools in identifying currently changing environmental conditions. Some species of forams (the Miliolida) produce calcareous shells with a chemical composition in equilibrium with seawater, and their shells are more soluble than shells of other species when exposed to reduced carbonate saturation. Thus, the abundance and diversity of such forams are good indicators of strong carbonate saturation, and they will likely be among the first to decline as rising atmospheric carbon dioxide concentrations result in progressive ocean acidification.

Many reef-dwelling forams contain algal symbionts similar to coral zooxanthellae, which give them color. Unlike corals that expel their symbionts, some forams consume their symbionts when exposed to too much sunlight. Because foram species are very specific in their ecological requirements, are relatively immobile, small, abundant, and easily sampled, scientists have developed a Foram Index that can be used to describe past and present ecological conditions of an area.

Scientists are currently studying the influence of local, regional, and global environmental changes associated with human activities to determine when foram assemblages respond in parallel with corals and when they do not. There is much hope that forams can serve as accurate predictors of environmental change.

Sand grain sources at coral reefs indicate reef health

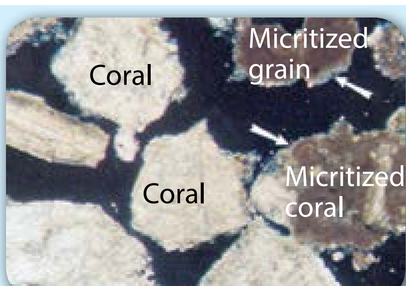
Barbara H. Lidz

The origin of sand grains gathered from along the Florida Keys Reef Tract can be used as an indicator of the overall health of the reef. The grains consist mostly of calcium carbonate that has been precipitated from seawater by reef organisms. Grain sizes range from mud and silt to gravel. Sediment grains mainly consist of broken shells, particles of calcareous algae, and coral sands. Coral-rich sands are produced from weathering and erosion of dead corals by organisms such as parrotfish, sea urchins, boring algae, barnacles, fungi, mollusks, and sponges. Wave action can redistribute the sands locally, but they generally remain near their place of origin. Percentages of grain types in a sample, except coral grains, represent the types of live organisms and their relative dominance in that local area.

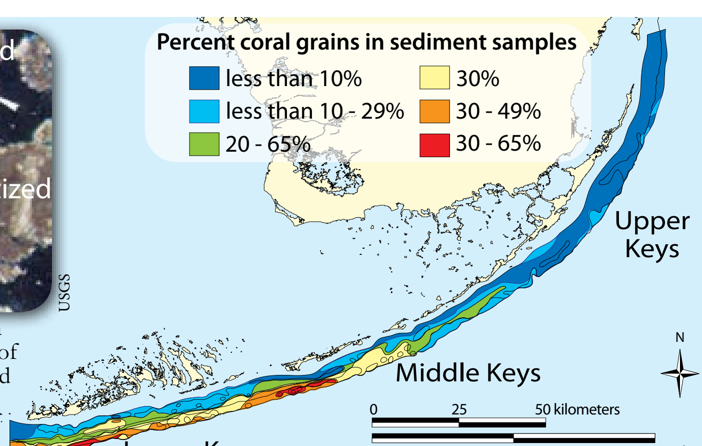
In 1989, a study examined the composition of sand grains at 143 sites off the Florida Keys. The results showed that the percentage of coral grains was correlated with the degree of observed reef decline: the higher the percentage of coral grains in the sample, the lower the frequency of live corals in that local area. Percentages of coral grains in the sands were also higher compared with earlier studies on sediment composition, indicating cumulative coral degradation.

A major finding of the study was that sediments at reefs opposite the widest tidal passes were richest in coral sands. Percentages of coral grains were highest in the Lower Keys outer shelf (65% of total sand grains), and that area had the highest percentage of observed dead corals. Off the Upper Keys, the percentages of fragmented calcareous algae and molluscan shells were greater than coral grain percentages.

Corals of the Lower Keys are topographically the most exposed to strong, cold, Gulf, and ocean currents. Also, tidal passes in the Lower and Middle Keys can deliver inimical turbid coastal bay waters that can affect the offshore reefs. Natural tidal passes are generally absent in the Upper Keys where the elongated islands shield offshore reefs from impacts of Bay and Gulf waters. Thus, reefs off the Upper Keys occupy relatively sheltered settings and are the healthiest on the reef tract, a condition that is reflected in relatively low percentages of coral sands in the sediments at those reefs.



Origin and composition of sands can be determined by viewing thin slices of grains under a microscope. Some sand grains have been chemically altered (micritized), and often their origins cannot be determined.



Percentages of coral grains in sands at reefs correlate positively with the amount of observed dead, skeletal coral.

Coral reefs provide important ecosystem services

James W. Porter

Nature's greatest architects

Corals are the master builders of nature. They build coral reefs and provide habitat for a wonderful diversity of life forms. By the simple act of depositing their calcium carbonate (i.e., limestone) skeletons, the cumulative effect is to build the largest and most topographically complex natural architectural creations in the living world. Coral reefs can be so large that they can be seen from outer space.

Image of Looe Key coral reef and a portion of the Lower Florida Keys. Coral reefs can be so large that they can be seen from outer space.

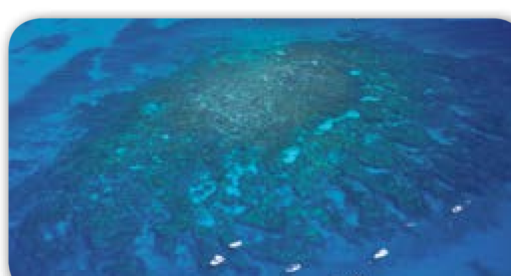
For every ounce of carbon dioxide (CO_2) fixed into organic material during coral photosynthesis, an equal weight of CO_2 is deposited as calcium carbonate into coral skeletons. Over millions of years, coral reefs have created massive fossil limestone formations found all over the world. Early civilizations depended on this "soft rock" because it could be cut into building blocks for homes, fortifications, and monuments. The Greek Acropolis, Mayan temples at Tikal, and the archaeological structures of Angkor Wat were all built from fossil coral reefs.

Nature's first line of defense

Coral reefs protect the coastline from the destructive effects of storms. During the catastrophic Indian Ocean Tsunami of 2004, towns along the coast of Sumatra behind healthy coral reefs suffered less destruction than towns with degraded offshore reefs. One of the predictions of global warming is for an increase in the intensity and, but with less statistical certainty, the number of hurricanes. Thus, protecting "nature's sea wall" may be as important a priority in hurricane preparedness in south Florida as increasing the capacity of evacuation routes.

Biodiversity hot spots

Coral reefs are extraordinarily diverse both at the species level and at higher levels of taxonomic classification. For example, of the 34 known animal phyla, 32 are found on coral reefs. Contrast that with the fact that only nine animal phyla are found in tropical rain forests. Rain forests have higher species diversity than coral reefs, but it is almost entirely based on the representation of species from one class of exclusively terrestrial organisms–the insects. Insects are by far the most diverse and most successful of all land animals. For instance, almost two



Aerial view of Looe Key, a bank reef in the Lower Florida Keys, showing topographic complexity and diversity of coral reef habitats, including spur-and-groove formations, deep reef, fore reef, reef crest, and back reef.

thirds of all described animal species on Earth are insects. However, there are no marine insects, which may be because on a comparative time scale, insects evolved relatively late in the history of the planet. Most evolutionary ecologists believe that by the time insects began to fall or crawl into the ocean, the many and already diverse denizens of the deep probably ate them before they could evolve into marine forms.

D.S. Gilliam - NSU

Coral communities, such as this one off Palm Beach County, Florida, have high biodiversity.

Drugs from the sea

Coral reefs are a pharmaceutical cornucopia. One quarter of all medicines on a drug store shelf come from the natural world, and a significant number of those come from the sea. Two of the most effective anti-cancer drugs on the market today were first extracted from Floridian reef organisms: Prostaglandin© from sea fans and Bryostatin© from bryozoa. Bryostatin© is useful in combating breast cancer, a leading cause of cancer-related mortality among women.

It is not a mystery why many pharmaceutical chemicals come from coral reefs. As the oldest and most diverse community on Earth, survival of the fittest has reached its pinnacle of expression on coral reefs. Tropical marine organisms produce more unique defense compounds than plants or animals from any other environment on Earth. These compounds protect reef organisms against attacks from other creatures. But as quickly as one chemical defense compound evolves, another potential chemical deterrent to this defense compound also evolves. This is the biological world equivalent of an evolutionary "arms race" that has been going on for millions of years on coral reefs.

An analogy between coral reefs and human societies

Although corals and humans are pretty much at opposite ends of biological organization, humans and human societies have more in common with corals and coral reefs than might initially be apparent:

- Humans and corals both evolved in the tropics.
- Corals tend zooxanthellae as a plant food source, and humans grow crops.
- Unlike many other animals, corals and humans are both herbivores and carnivores.
- Human and coral skeletons are made from calcium.
- Both corals and humans build with limestone, and both edifices are prone to damage by hurricanes.

However, among many differences, several stand out:

- The high productivity of coral reefs is due to the preservation of high species diversity. By contrast, most productive human landscapes are monocultures of rice, corn, or wheat.
- Corals farm their plants inside their cells; humans cut down the natural world to make way for their crops.
- Coral reefs have survived for at least 250 million years. Will humans make it that long?

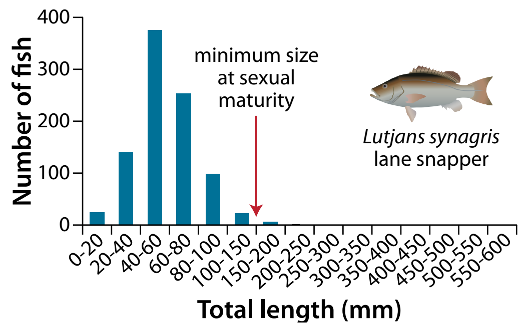
By their amazing diversity and impressive longevity, coral reefs set a high standard on how to survive on Planet Earth (or "Planet Ocean," as corals may prefer it be called). Perhaps another value that coral reefs provide is to remind humankind that the best way to create sustainable communities is to preserve the diversity of life in and around them. Earth is our shared home, and coral reefs and other natural environments depend on humans to "get it right."

The nearshore hardbottom community provides critical habitat for juvenile fishes in the Florida Keys

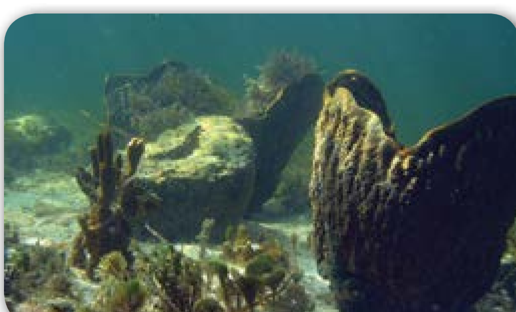
Marie-Agnès Tellier

Hardbottom habitat is one of the most common marine communities in south Florida. It is characterized by a solid substrate (i.e., rock) that is colonized by an epibiotic (attached) community consisting of algae, sponges, octocorals, stony corals, and other animal groups. Hardbottom habitat can be found from subtidal areas to the edge of the continental shelf.

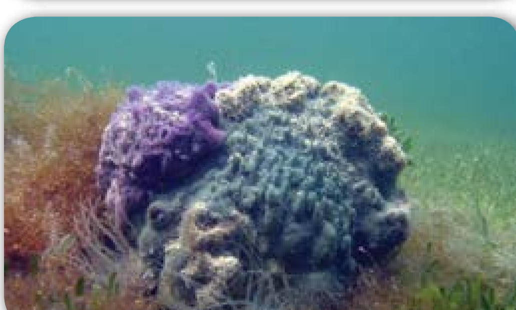
Nearshore areas in the Florida Keys are partially characterized by a combination of hardbottom and hardbottom mixed with seagrass habitats that cover approximately 67,000 hectares (165,560 acres) or approximately 29% of nearshore habitats. Within 2 kilometers (1.2 miles) from shore, the nearshore hardbottom habitat is characterized by a solid, low-relief limestone platform, supporting a diverse assemblage of sponges, corals, octocorals, and solution holes that provide varying degrees of structural complexity favorable to fish and motile invertebrates. These biological and physical structures provide both shelter and foraging habitat.



Size-class distribution of lane snapper collected from nearshore hardbottom habitat in the Florida Keys. Approximately 99% of the lane snappers collected on hardbottom habitats were juveniles that were smaller than minimum size at sexual maturity.



R.D. Bertelsen - FWC



R.D. Bertelsen - FWC

Nearshore hardbottom (top) and hardbottom mixed with seagrass (bottom) habitats are critical for juvenile fishes in the Florida Keys.

During a recent survey of hardbottom habitats in the Florida Keys, more than 32,000 fish were observed among 186 species. Eighty-nine percent of the fish collected were smaller than 150 millimeters (6 inches) total length, and approximately 75% of the fish were less than 25% of their adult maximum size. More than 90% of reef fish species observed were juveniles, including white grunts (*Haemulon plumierii*), gray snappers (*Lutjanus griseus*), lane snappers (*Lutjanus synagris*), yellowtail snappers (*Ocyurus chrysurus*), red groupers (*Epinephelus morio*), and gag groupers (*Mycteroperca microlepis*).

The nearshore hardbottom habitat is susceptible to impacts from fishing, diving, and snorkeling activities; climatic events, such as hurricanes; and pollutants from land-based sources. An understanding of the importance of the nearshore hardbottom habitats in the life history of commercially and ecologically important fish species is essential for informed management of the Florida Keys marine ecosystem.

Corals have inspired major biotechnological advances

Max Teplitski

In aquaria as well as in natural environments, corals can emit a fluorescent glow under the right illumination. This occurs because corals contain fluorescent proteins that absorb certain wavelengths of light and then glow at a different hue. Corals make fluorescent proteins in every color of the rainbow, and their discovery has revolutionized biotechnology. For example, scientists are using the coral genes that encode a fluorescent protein as a marker to track gene expression in plants, animals, and even bacteria.


M. Matz - UT

Corals emit a fluorescent glow under the right illumination as seen in this elkhorn coral. Scientists are using the ability of coral pigments to change colors to make exquisitely sensitive detectors of toxins, drugs, and explosives. Fluorescent coral pigments are being used to track regulation of genes required for disease resistance, organ development, and physiological changes that result in cancer or other diseases.

Use of such easily traceable fluorescent markers is especially important in learning how diseases develop in order to then specifically block or disrupt the disease progression. Fluorescent reporters are also used in the battlefield. For example, fluorescent protein markers were engineered into a gene that responds to explosives. That gene was then placed into a short-lived weedy relative of the mustard plant and the seeds of that plant were scattered over minefields. When the seedlings sprout, they emit a fluorescent glow only when growing next to an explosive landmine, making landmines easy to detect and ultimately disarm.

Even though corals lack simple physical deterrents, such as spines or shells, they are not defenseless. They have evolved a sophisticated biochemical arsenal that they use as a shield against predators and pathogens. Scientists have begun to recognize the unique pharmaceutical potential of chemicals produced by corals and other marine invertebrates. A collection of tens of thousands of purified compounds and mixtures from sea creatures is maintained by the National Cancer Institute. Researchers have identified many novel anti-inflammatory, cancer-fighting, and antibiotic compounds using chemicals contained in that collection. Further research will identify additional chemical scaffolds upon which new classes of pharmaceuticals will be built.

Corals produce a skeleton that is made of a calcium carbonate mineral called aragonite. Properties of aragonite are attractive to both medical and material scientists. Tiny granules of aragonite embedded into a titanium mesh are being tested for their ability to induce regeneration of bones. Corals make aragonite using only seawater and dissolved calcium and carbon dioxide. Factory synthesis of aragonite, on the other hand, currently requires a step with temperatures as high as 900°C (1650°F) as part of the development process. Because aragonite can be used as an additive to cement, engineers are investigating its production by mimicking what corals do, using seawater and sequestering CO_2, a greenhouse gas, from fossil-fueled power plants.

Unlocking the mysteries of corals has already resulted in progress in several fields of science. Responsible bioprospecting of corals will surely continue to open new scientific horizons.

Coral reefs provide economic value

Grace M. Johns

Coral reefs have many values, including value in recreation, commercial seafood harvest, and the value people place on knowing that coral reefs are healthy for future generations to enjoy. An economic study of the value of south Florida coral reefs was conducted in 2001 – 2003. For simplicity, all values are for 2001.

J. Luo - UM/RSMAS

SCUBA diving is a popular activity at coral reefs.

Residents and visitors spent 18.7 million person-days on southeast Florida coral reefs in 2001. A person-day is one person participating in a reef-related activity for all or part of 1 day. Approximately 9.8 million person-days were spent by residents and 8.9 million person-days were spent by visitors. The most used coral reefs are in Miami-Dade County, with 6.2 million person-days annually.

County	Residents	Visitors	Total
Martin	210,000	59,000	269,000
Palm Beach	1,901,000	930,000	2,831,000
Broward	2,437,000	3,030,000	5,467,000
Miami-Dade	2,965,000	3,250,000	6,215,000
Monroe	2,277,000	1,600,000	3,877,000
Total	9,790,000	8,869,000	18,659,000

Number of person-days spent recreating on coral reefs in southeast Florida by county in 2001.

About one half of these person-days was spent recreational fishing, and about one quarter each was spent snorkeling and SCUBA diving. Recreators in the five counties spent 9.7 million person-days fishing on coral reefs, 4.2 million person-days snorkeling, and 4.6 million person-days SCUBA diving in 2001.

County	Fishing	Snorkeling	SCUBA	Total
Martin	213,000	31,000	25,000	269,000
Palm Beach	1,148,000	418,000	1,266,000	2,832,000
Broward	2,582,000	838,000	2,007,000	5,427,000
Miami-Dade	3,965,000	1,484,000	753,000	6,202,000
Monroe	1,825,000	1,469,000	510,000	3,804,000
Total	9,733,000	4,240,000	4,561,000	18,534,000

Number of person-days spent recreating on coral reefs by activity and county in 2001.

People who fish, snorkel, and SCUBA dive on coral reefs receive value from that experience that can be measured in dollars by their expenditures to use the reefs and their willingness to pay an additional amount to be assured that coral reefs will be maintained in their existing condition. The expenditures made by these recreators in 2001 totaled an estimated $1.9 billion and included charter boat fees, fuel, bait, tackle, ramp fees, marina fees, lodging, food, beverages, and equipment rental. The annual willingness to pay to protect coral reefs in their existing condition totaled an estimated $233 million. Thus, the total value of coral reefs in southeast Florida to recreators who used the reefs in 2001 was $2.1 billion.

County	Dollars spent	Pay to protect	Total value
Martin	$10	$4	$14
Palm Beach	262	42	304
Broward	708	83	791
Miami-Dade	571	47	618
Monroe	342	57	401
Total	$1,894	$233	$2,127

Annual value of coral reefs in southeast Florida in millions of dollars in 2001.

Corals are a potential tool in measuring climate change

Eugene A. Shinn

Will climate change cause corals to go extinct, or will they begin colonizing cooler waters? No one can give a definitive answer to that question today, but some simple experiments and observations have contributed to our understanding of this topic. Above all, these observations demonstrate that corals are hardy, but temperature sensitive, and may serve as indicators of climate change. Because the geographic ranges and abundance of corals have varied significantly over geologic time, there is a need for close collaboration among biologists and geologists in studying factors influencing the long-term and short-term population changes in corals.

Temperature tolerances of some coral species

In 1914, Alfred Mayer (Mayor) measured temperature tolerances of some hard coral species. Some 50 years later, a simple *in situ* experiment confirmed Mayor's results for staghorn coral (*Acropora cervicornis*) and demonstrated why that species does not grow nearshore in the Florida Keys. Staghorn coral was transplanted to a nearshore area, and seasonal water temperatures were found to fluctuate more than in offshore waters. The nearshore transplants grew at the same rate as corals found offshore until summer when nearshore corals bleached, expelling their zooxanthellae and retarding their growth rate. They survived summer temperatures of 33.8°C (93°F) for 2 months.

Coral species	Low survival temperature		High survival temperature	
	°C	°F	°C	°F
Staghorn coral	14.1	57.4	36.8	98.2
Elkhorn coral	no data		35.7	96.3
Symmetrical brain coral	15.3	59.5	37.7	99.9
Boulder star coral	16.0	60.8	36.2	97.2
Mustard hill coral	no data		36.7	98.1
Thin finger coral	10.2	50.4	38.2	100.8
Lesser starlet coral	1.8 – 6.7	35.4 – 44.0	38.2	100.8
Massive starlet coral	11.5	52.7	37.8	100.0

Mayer (Mayor) (1914, 1915, and 1918)

Survival temperatures of some common coral species.

Coral species	Temperature	
	°C	°F
Elkhorn coral	17.4 – 17.8	63.3 – 64.0
Thin finger coral	14.5 – 14.7	58.1 – 58.5
Lesser starlet coral	10.5 – 17.3	50.9 – 63.1
Rose coral	16.3 – 18.6	61.3 – 65.5

Mayer (Mayor) (1915)

Temperatures at which corals lost their ability to capture food.

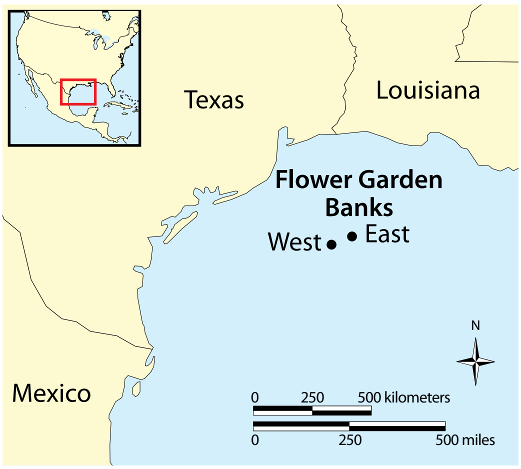
W.C. Jaap - FWRI

W.C. Jaap - FWRI

Top: Staghorn coral thicket at Loggerhead Key, 1965. Right: Dead staghorn rubble after 1977 cold-water event.

Coral Reefs and Hardbottom Habitats

However, after the transplants regained their zooxanthellae, a winter cold front lowered nearshore water temperature to 13.3°C (56°F), and the nearshore corals died. In addition, the study found that the growth rate of offshore staghorn corals



Location of Flower Garden Banks National Marine Sanctuary.

increased during summer months (30°C [86°F] maximum) and slowed during winter months when temperatures reached 27.7°C (82°F). Thus, staghorn coral is a relatively sensitive indicator of temperature, which is a main factor controlling its local distribution.

Several other coral transplant studies have been performed that help to define temperature tolerance and the future survival of several species of corals. In the late 1960s, elkhorn coral (*Acropora palmata*) was transplanted from Florida to Bermuda where the species is naturally absent. That experimental transplantation was conducted twice, and in both cases low water temperatures in winter killed the transplants. It is possible that with warming seas, *Acropora* species could colonize Bermuda if coral larvae can live long enough to make the oceanic journey.

In the mid-1970s, boulder corals (*Montastraea annularis*), were transplanted to nearshore locations in the Florida Keys. The transplants closest to shore died during a severe cold period in 1977. During that period, water temperatures dropped to 8.8°C (48°F), and snow fell in Miami. The growth rate of offshore corals that survived was retarded. This cold period killed massive stands of staghorn coral, such as those at Loggerhead Key, where it has yet to recover.

Elkhorn coral was also transplanted to an experimental reef site at Flower Garden Banks National Marine Sanctuary in the northwestern Gulf of Mexico. The corals survived the transplantation, but researchers removed them because they were not part of the local ecosystem as it exists today. More recent research discovered that elkhorn and staghorn grew at the Flower Garden Banks about 6000 years ago during the Holocene thermal maximum, a time when global temperature is believed to have been higher than today. Recently, two living elkhorn colonies have been found at the Flower Gardens. These observations support the theory that global warming may result in the return of large numbers of acroporid corals to the Flower Garden Banks.

In addition to transplant studies, geological observations of fossil corals give clues to their environmental tolerances. A large shelf edge *Acropora* reef flourished off Fort Lauderdale until about 7000 years ago. This extinct reef is at a depth of between 14.9 – 17.9 meters

W.F. Precht - FKNMS

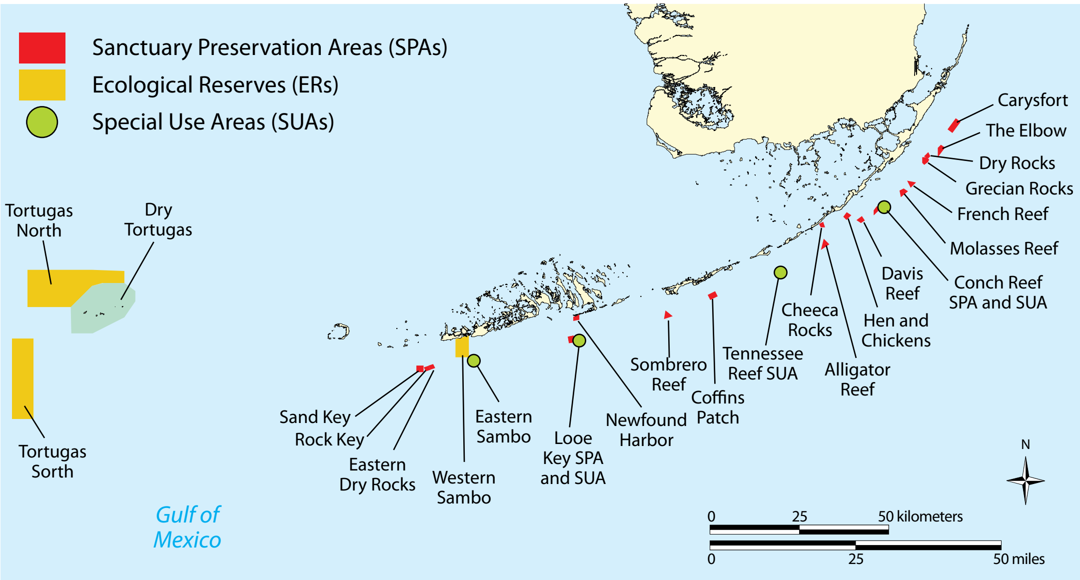
Living elkhorn coral colony recently discovered at Flower Garden Banks National Marine Sanctuary.

(49 – 59 feet). Dating of a fossil elkhorn coral at Cobblers Reef off Barbados revealed that the reef was alive from 4500 years ago to about 350 years ago. Both the Fort Lauderdale and the Barbados reefs disappeared long before impacts by human populations. Research suggests that the situation in Barbados may have been due to a period of intense hurricanes. Did climate change, sea-level rise, or both play a role? We do not know and must attempt to learn from these geological observations in order to understand recent coral demise.

Further evidence of periodic declines in coral cover was provided by a study where 39 fossil staghorn coral pieces from 19 sites along the Florida Keys Reef Tract were dated. The results revealed two periods where staghorn coral was absent, each lasting approximately 500 years. One gap occurred approximately 3000 years ago, and a more pronounced gap occurred 4500 years ago. What caused the mortality of this species? Are we now seeing a repeat of former die-offs?

Present-day coral reefs

The present-day reefs that are found along the Florida shelf margin facing the Florida Straits consist of coralline spurs built primarily by elkhorn corals that grew directly on the underlying Pleistocene limestone. Many of these true Holocene reefs are marked with lighthouses in the Florida Keys. The scattered distribution of all Holocene reefs (less than 1% of the area of the Florida Keys Reef Tract) and extensive skeletal veneers along the platform margin of reefs that did not reach sea level indicate periodic interruptions of Holocene coral growth. Given uninterrupted growth, even the slowest-growing coral species should have kept pace with sea-level rise during the past 6000 years. The faster-growing branching corals could have easily outpaced the rise, but they have not, and we do not know why. Dating has revealed that most Holocene reef spurs ceased growing about 2000 years ago, and their composition has become overgrown by fire corals, sponges, and gorgonians. The thickest Holocene reefs are those that have kept pace with rising sea level and occur in discontinuous rows landward of the platform margin in places like Grecian Rocks and Key Largo Dry Rocks in the Upper Keys. Reefs there are up to 14.9 m (49 ft) thick.



Location of well-known Holocene reefs in the Florida Keys.

Coral reefs throughout the wider Caribbean basin are in decline

Margaret W. Miller

Imagine that four out of every five trees in all the forests of an entire continent died and did not appear to be regrowing. Coral reef decline is occurring similarly to such a hypothetical scenario throughout the Atlantic and Caribbean basins, including south Florida. Coral cover throughout the Caribbean region has decreased from an overall average of more than 35% live coral cover in the 1970s to around 10% in 2000s. The overall average live coral cover throughout the Florida Keys Reef Tract was only 6.1% in 2006.

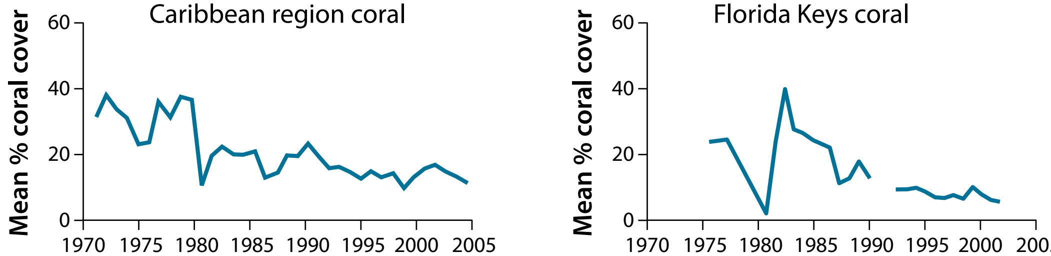
Declines in branching corals occurred in the Dry Tortugas prior to 1977, likely from natural stresses such as storm damage and cold winters. Although precise data on Keys reef status are not abundant prior to the mid-1990s, it is clear from studies at a few individual sites that rates of decline in live coral cover for Florida Keys reefs continue at high levels through the present. Similar loss of live coral has even been observed in some areas that are remote from land-based human impacts, suggesting that large-scale environmental changes, such as global warming and local human activities are degrading reefs.

Corals are not the only component of the reef ecosystem that is in trouble. Humans have removed fishes, conch, and lobster from coral reefs, causing a cascading effect on the ecosystem. Although it is difficult to know how reefs looked before modern times, it is likely that large animals that are rare or extinct today, such as green turtles, manatees, large sharks, and monk seals, played important roles in Caribbean coral reefs of the past.

Long-spined sea urchins (*Diadema antillarum*) are crucial reef grazers that maintain clean substrate for corals and other reef invertebrates to recruit and grow. Over 90% of these urchins died between 1982 – 1983 throughout the entire Caribbean region and have not recovered in the Florida Keys. The loss of large populations of important grazing animals to the reef ecosystem is one of the primary impacts that has resulted in declines in Caribbean and south Florida coral reefs.

Stresses to Florida coral reefs

Florida reef communities are growing at the northern temperature limits of reef development, subjecting them to high levels of naturally occurring stresses, such as cold winters. Additional stresses are imposed by large human populations living, recreating, and using the coastal environment.



From Schutte et al. (2010)

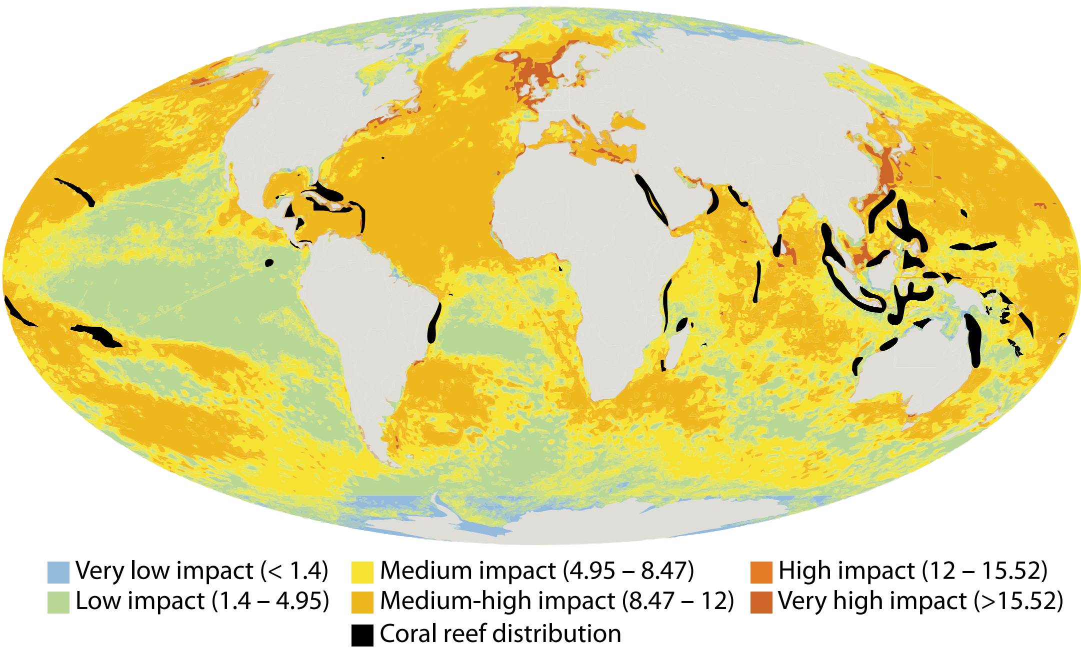
Summary of measurements of live coral cover from combined studies on Caribbean (left) and Florida Keys (right) reefs. Coral cover, averaged throughout the Caribbean region, declined from a mean of more than 35% in the 1970s to about 10% in the 2000s. Overall coral cover in the Florida Keys probably started around 25% in the 1970s and has declined to around 5%. Although the trend averaged across many sites shown here appears fairly stable since about 1995, individual reefs have continued to show precipitous declines from intermittent catastrophic events.

Global stressors are impacting coral reefs

Andrew C. Baker

Coral reef ecosystems are severely threatened by the impact of human activities. Although some of these threats are local, affecting relatively small reef areas or regions, some threats are global and are having large-scale effects on reefs around the world. These global threats include overfishing, climate change, ocean acidification, and disease.

fish that grow and live on coral reefs as a significant source of food. Only a few reef areas, such as the Line Islands in the Pacific Ocean and the Chagos Islands in the Indian Ocean, have escaped the worst effects of overfishing principally because of their remote location and small number of human inhabitants. Unless large-scale efforts are undertaken to protect these



Coral reef distribution and the severity of human impacts to the worldwide oceans. Measures of the impact of human activities range from very low (<1.4) to very high (>15.52).

Overfishing and overharvesting are perhaps the oldest threats to coral reefs. Historically, their impacts were confined to local reef areas close to human populations, but in recent decades, overfishing has become a truly global problem, with significant impacts on reefs worldwide. Large consumer species, such as turtles, sharks, and other large carnivorous and herbivorous fish, are now significantly reduced both in size and in numbers on virtually all coral reefs. Today, over a billion people worldwide rely on areas from fishing, as was announced for the Chagos Islands in April 2010, it is likely that even these relatively pristine reef communities will be affected as global commercial fisheries expand their ranges.

Climate change is a more recent and even more severe global threat to reefs. The emission of greenhouse gases, principally carbon dioxide from the burning of fossil fuels, is resulting in warmer oceans. Warming is a threat to corals because the fragile partnership that exists between corals and their symbiotic algae (i.e., zooxanthellae) breaks down when corals are exposed to temperatures only a degree or two above the normal summertime maximum. This disruption of coral-algal symbiosis results in coral reef bleaching, in which corals lose their zooxanthellae and turn pale or white.

A.C. Baker - UM/RSMAS

When corals are stressed by warm temperatures, they can loose the symbiotic algae that give corals their color. If bleaching is severe or prolonged, bleached corals will eventually die. However, if conditions quickly return to normal, bleached corals can recover, usually within a few weeks.

Episodes of mass coral reef bleaching have occurred in one or more of the coral reef regions in the world almost annually for the past 30 years, with particularly strong events resulting in widespread death of corals in the eastern Pacific in 1982 – 1983, the western Indian Ocean in 1997 – 1998, the Great Barrier Reef in 2002, and the eastern Caribbean in 2005. With global warming scenarios indicating further warming of 2° – 4°C (3.6° – 7.2°F) by 2100, it is likely that coral reefs will be devastated by the impact of repeat episodes of severe coral bleaching unless significant adaptation or other response mechanisms allow them to accommodate warming temperatures.

In addition to global warming, increases in atmospheric carbon dioxide also lead to ocean acidification because carbon dioxide dissolves in seawater and lowers its pH. The acidification of the oceans makes it more difficult for corals (and other calcifying marine organisms) to build their calcium carbonate (i.e., aragonite) skeletons. Weaker skeletons that grow more slowly are believed to hinder the ability of corals to compete with other reef organisms and build reef structures that provide ecosystem habitat.

It is anticipated that the oceans will become increasingly acidic in the future as carbon dioxide emissions continue. Although the tropical shallow waters where coral reef ecosystems are found will be the slowest to respond to acidification, it is nevertheless clear that without dramatic reductions in emissions, ocean acidification will make it more difficult for corals to bounce back from disturbance as a result of other global and local stressors, including coral bleaching.

NOAA

Corals weakened by bleaching or other stressors may be more susceptible to other diseases, such as black-band disease shown here. In addition, pathogen development and transmission may be accelerated at higher temperatures.

A further global threat to reefs that may be driven by greenhouse gases is the emergence and spread of marine diseases, which seem to be linked to the warming of the worldwide oceans as a result of climate change. Corals weakened by bleaching and other stressors may play a part in explaining this trend, but it is also possible that pathogen development and transmission rate is increased at higher temperatures, leading to disease outbreaks.

Coral reefs are being affected worldwide as a result of these threats. These threats make it even more important for us to reduce local stresses to coral reefs, such as poor water quality and habitat destruction, so that these ecosystems have a fighting chance of surviving through this century.

Fifty years of coral boom-and-bust at Grecian Rocks shows changes in the coral reef

Eugene A. Shinn

E.A. Shinn - USGS

E.A. Shinn - USGS

E.A. Shinn - USGS

E.A. Shinn - USGS

E.A. Shinn - USGS

The images shown are selected from a 50-year time series (1960 – 2010), taken at Grecian Rocks reef off Key Largo. The images document the drastic demise of staghorn coral (*Acropora cervicornis*) that began in 1979 and peaked in 1983 – 1984.

Coverage of staghorn coral at this site expanded rapidly following the passage of Hurricane Donna (1960) and continued in spite of Hurricane Betsy (1965). Rapid growth continued until 1978 when staghorn coral almost covered the boulder coral (*Montastraea* spp.) shown in all of the photographs.

A study conducted at this site in 1960 revealed that staghorn grew at an average rate of 10 centimeters (4 inches) per year, and that growth rate was affected by annual temperature fluctuation. An average of three new branches formed from the terminal polyp each February and grew 10 cm (4 in) before repeating the branching process the following winter. At that rate, a clump of 10 branches could potentially proliferate into 56 kilometers (35 miles) of branches in only 10 years!

Branches that grew to within a centimeter of the *Montastraea* coral were attacked and killed by the *Montastraea* head, demonstrating the ability of *Montastraea* to fend off faster-growing branching corals by attacking with defensive mechanisms.

By 1979, acroporids everywhere in Florida were beginning to show signs of stress and disease. There were no living branching corals at this site on Grecian Rocks by 1988. Similar observations were photographically documented at Carysfort Reef, and synchronous demise of acroporids occurred in 1983 at San Salvador, eastern Bahamas. The *Montastraea* head shown in these photographs is only partially alive in 2010 and its morphology has changed radically.

Is nutrient pollution killing Florida coral reefs?

Steven L. Miller and William F. Precht

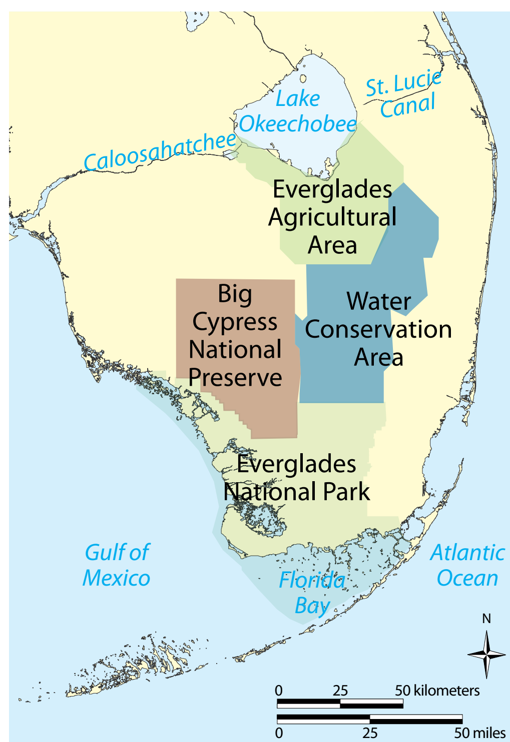
Declining water quality often is cited as the primary cause of stress to south Florida coral reefs. Indeed, coral reefs can grow and thrive only in areas that are not limited by degraded water quality. Increases in the abundance of benthic macroalgae observed on some bank reefs in the Florida Keys support an assumption that nutrient pollution from land-based sources may be the cause of increased algal growth. However, it is more complicated than that, and no studies have conclusively linked increased algal growth on reefs in the Keys with discharges from land-based sources of nutrients.

M.A. Moe Jr. - MML

The reduction in grazing due to the loss of a major herbivore on south Florida reefs, the long-spined sea urchin, has undoubtedly resulted in growth of benthic macroalgae on some reefs that is unrelated to nutrient influxes.

Some recent evidence using viral tracers shows that it is probable that nutrients may be delivered to offshore reefs in the Keys with groundwater. However, surface water samples fail to detect increased nutrient concentrations. Studies on injection wells in the Keys have shown that wastewater nutrients are diluted by more than a million to one by groundwater close to the injection point. Much more dilution must result with the transfer of groundwater offshore. Long-term water quality data taken at bank reefs show that, in general, water quality is good and has not decreased over the past 15 years, which bolsters the argument for other reasons for observed increases in algal cover.

The amount of nutrients delivered to offshore reefs must be evaluated relative to other nutrient influxes, such as the Gulf Stream flow, tidal flushing, and upwelling. Frequent cold-water upwelling events regularly deliver high volumes of nutrient-rich water to the fore reef in the Florida Keys. These events deliver water with 10- to 40-fold higher nutrient concentrations than published estimates of influxes to nearshore waters from wastewater and stormwater. Thus,



Most water discharged from the Everglades Agricultural Area flows through Everglades Conservation Areas and Everglades National Park before reaching marine waters. There is little chance that nutrient pollution from the Everglades Agricultural Area is adversely affecting coral reefs of south Florida.

Nutrient-enriched water discharged from agricultural areas into Everglades wetlands results in a conversion of the native sawgrass communities to cattails. Most water discharged from the Everglades Agricultural Area flows through Everglades Conservation Areas and Everglades National Park before reaching marine waters.

the Florida Keys Reef Tract has been historically and periodically subjected to high concentrations of nonanthropogenic nitrogen and phosphorus. Currently, pollution from remote sources via the Gulf Stream system is not considered a major problem but remains an issue that must be carefully watched. Oil spills and floodwaters carrying pollutants to the Gulf of Mexico are a potential threat to downstream ecosystems, including the coral reefs of south Florida.

In the past few thousand years, coral reef development in the Florida Keys has been greatest seaward of the islands compared to seaward of the tidal passes. It is believed that water exiting the broad shallow expanses of Florida Bay through the tidal passes between the Keys was hot enough in the summer and cold enough in the winter to stress or kill reef-building corals. One would expect a similar effect today, with coral assemblages being healthier and more robust where the Keys block the flow of water out of Florida Bay. However, this is not the case; essentially all reef communities of the Keys, even those blocked from Florida Bay, have been in decline. It is most probable that the main causes of the widespread regional decline are from global stressors, including climate change.

Nutrient pollution from the Everglades Agricultural Area south of Lake Okeechobee has been cited by some as a primary factor of coral reef decline in south Florida, including the Florida Keys. Although nutrients discharged from the Everglades Agricultural Area have significant local effects on the Everglades, they have no or minimal impacts on the southern reaches of Everglades National Park and Florida Bay. Therefore, impacts of agricultural runoff on offshore reefs, located even farther away from the source, are highly unlikely. Significant management attention is being focused on restoring the quality, quantity, timing, and distribution of water from upstream sources to the Everglades. If done correctly, these efforts can only improve water quality filtered through the Everglades and discharged to Florida Bay and beyond.

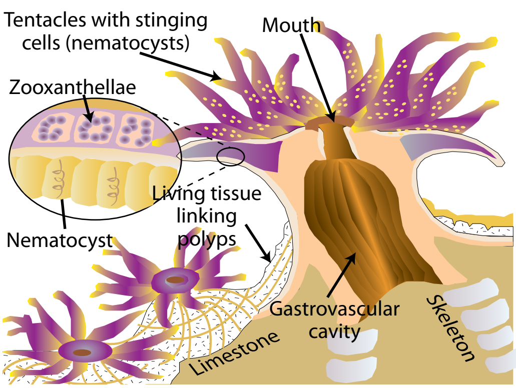
Microbial communities are important to corals

Kim B. Ritchie

Although it has been known for some time that microbes can cause coral diseases, scientists are beginning to realize that many microbes, including bacteria, form beneficial associations with corals and are important for coral health.

Bacteria were the first living organisms on Earth, and fossil records show their presence for at least 3.5 billion years, that is about 2 billion years before higher organisms emerged. Bacteria are responsible for the accumulation of oxygen in our atmosphere, the evolution of higher organisms, and many processes on earth that make life as we know it possible. Because the majority of evolution took place in the oceans, where life first began, there has been ample time for the evolution of beneficial associations between bacteria and marine invertebrates.

Corals produce mucus that coats the outsides of their polyps. This mucus is used for protection, much like the mucosal linings of human membranes. When corals become covered in sediments, they produce mucus in sheets so that foreign material can be sloughed away. Coral mucus also protects the coral from sun damage and from drying out if exposed to air at low tides. Coral mucus even contains antibiotic properties to help prevent infections to corals.



Structure of a coral polyp.

Corals, such as this healthy elkhorn coral at Carysfort Reef in 2008, harbor beneficial bacteria that may provide resistance to invasion by foreign microbes, including those that cause coral diseases.

Nutrients in the slimy mucus attract a large number of bacteria that find food and shelter there.

Different coral species produce a specific composition of mucus that is believed to attract specific groups of beneficial bacteria. These bacteria are believed to provide important protective, metabolic, and nutritional functions. Resident bacteria are believed to help corals resist invasion by pathogens by preventing attachment and entry into coral cells or by competing for nutrient availability, thereby maintaining the optimal microbial balance. Also, it is now known that some of these bacteria produce antibiotics that may help corals to resist diseases.

When corals are stressed by an increase in ultraviolet light, temperature change, or other factors, they become more susceptible to illnesses, including attack by opportunistic pathogens. It has been shown that some of the more sensitive corals, such as elkhorn coral (*Acropora palmata*), lose immunity when temperatures increase. A rise in the abundance of potentially pathogenic coral bacteria (*Vibrio*) has also been documented during times of increased temperatures. Coral stress and loss of immunity, together with an increase in opportunistic coral pathogens during times of greatest stress, may explain why corals are much more sensitive to disease and decline during times of heat stress.

Coral diseases are a major cause of coral death

Deborah L. Santavy and Esther C. Peters

Corals are susceptible to diseases

Some coral diseases are associated with pathogenic bacteria; however, the causes of most coral diseases remain unknown. Some diseases trigger rapid and extensive mortality, whereas others slowly cause localized color changes or injure coral tissue, but recovery can occur. Several coral diseases involve the symbiotic algae harbored in the coral tissue. Although causes vary, all diseases occur in response to biotic stresses, such as bacteria or fungi, or abiotic stresses, such as changes in sea temperature, pollutants, or terrestrial runoff. Most probably result from multiple stresses that can reduce coral immunity and promote increased disease-causing microorganisms.

The increase of coral disease in recent decades caused widespread mortality of many coral reefs in the Florida Keys and Caribbean, leading some scientists to predict their ecological extinction in this century if the trend persists. Widespread mortality can eliminate entire coral species and replace them with more tolerant ones, resulting in loss of habitat for many reef fish and invertebrates. Often, replacement species are not major reef-building corals.

A 1998 – 2006 study that assessed coral health from Biscayne Bay to the Dry Tortugas concluded that low incidences of coral diseases were widespread, with only 15% of the area containing no disease. White-pox outbreaks at Looe Key in 1998 affected almost half of the elkhorn corals (*Acropora palmata*) and coincided with the worst coral bleaching in Florida. Both of those events caused extensive coral mortality in the Keys, with significant declines of elkhorn, staghorn (*Acropora cervicornis*), and boulder corals (*Montastraea* spp.). The dominant coral diseases found were white pox, dark spot, white band, and white plague. Most coral diseases have been aptly named based on the color or pattern of the affected coral tissue.

D.L. Santavy - EPA

D.L. Santavy - EPA

Black-band disease. Black-band disease was the first coral disease described and was found during the 1970s in the Florida Keys. Infected stony corals and sea fans have a compact black band covering the margin of healthy tissue next to tissue-depleted bare white skeleton. The band is a microbial mat comprising filamentous blue-green algae (i.e., cyanobacteria) and many different types of bacteria that secrete toxins and create an anoxic (i.e., no oxygen) environment, killing coral cells. Black-band disease infects mostly boulder corals but can infect other species. Many corals at Looe Key, Florida were infected with black-band disease during the 1980s and died.

D.L. Santavy - EPA

Coral bleaching. When stressed by extreme seawater conditions, corals lose their symbiotic algae and become bleached. The photosynthetic pigments of algae give corals their characteristic colors. After corals bleach, the tissue becomes translucent, and the white coral skeleton beneath is revealed. Some corals, such as fire corals, are more susceptible to bleaching than others. Genetic and environmental factors trigger some individuals, colonies, and species to respond differently. The most severe bleaching in the Florida Keys occurred during the summers of 1997 and 1998. Bleaching often is attributed to increased seawater temperatures, ultraviolet light, and calm sea conditions and is associated with global climate change and El Niño events. Prolonged bleaching can cause partial to total colony death. If stressful conditions cease after a short time, colonies often can reacquire their symbiotic algae and survive.

D.L. Santavy - EPA

Dark-spot disease. Diseased tissues appear as purple, gray, or brown irregular lesions over the colony surface, which slowly enlarge from their centers and can cause tissue mortality. Darkened areas often are depressed and contain smaller-than-normal polyps. Dark-spot disease affects massive starlet (*Siderastrea siderea*), blushing (*Stephanocoenia intersepta*), and boulder star (*Montastraea annularis* complex: *M. annularis*, *M. faveolata*, and *M. franksii*) corals.

D.L. Santavy - EPA

Red-band disease. Red-band disease is similar to black-band disease, except the band is red to maroon in color and is caused by different cyanobacterial species. Unlike black-band disease, the band can be compact or diffuse, resembling a web-like net adjacent to healthy tissue and tissue-depleted skeleton. Red-band disease infects massive and plating corals through the Caribbean basin and is especially prevalent on sea fans in the Florida Keys.


A. Bruckner - NOAA

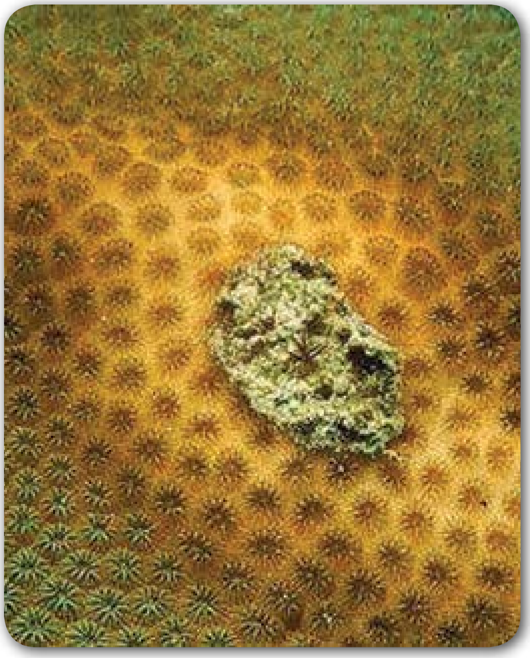
White-band disease. White-band disease only affects Caribbean acroporid species, staghorn (*Acropora cervicornis*) and elkhorn (*A. palmata*) corals. The tissue uniformly sloughs off the coral skeleton, usually progressing from the colony base to the branch tips. Bacterial aggregates are found at the tissue-skeletal interface and are believed to play a role in white-band disease. This disease caused extensive mortality in acroporids throughout the Caribbean and Florida in the past several decades. Decline due to white-band disease is one reason cited for listing these corals as threatened species under the federal Endangered Species Act.


D.L. Santavy - EPA

White-pox disease. White-pox disease, also known as white-patch disease, only affects elkhorn coral (*Acropora palmata*) in Florida and the Caribbean. It was first reported in 1996 near Key West. Irregularly shaped bare skeleton appears scattered over the colony, and the skeleton can be eroded or intact. The cause of the disease has been identified as the bacterium *Serratia marcescens*, which is common in the human intestine and the environment.


G.P. Schmahl - NOAA

White plague. White plague has similar features to white-band disease. It affects up to 45 Caribbean coral species but not the acroporids. The disease is characterized by large white areas of skeleton exposed by recent tissue mortality. The exposed skeleton usually is stark white because of recent and rapid tissue destruction, up to 2 cm (1 in) per day along the tissue loss margin. White plague lesions usually originate at the colony base and progress toward the center. The rapidly spreading disease appears to have originated in the Florida Keys. It was first reported in 1977, with another outbreak recorded in 1995.


E.C. Peters - GMU

Caribbean yellow-band disease. This disease affects star corals (*Montastraea* spp.) and brain corals. It was first described in 1994 from the Lower Keys but is now known to occur throughout the Caribbean. First, the affected tissue appears as a pale-yellow patch. As the disease progresses, a yellow band of tissue forms at the outer edges of the original patch, and white skeleton is exposed in the center of the infection site. Corals can be infected for many years, and the disease can affect multiple locations on a colony. The cause of the disease is a consortium of bacteria that kills most of the symbiotic algae, resulting in paled tissue retaining a yellowish color.

Corals can have growth anomalies

Esther C. Peters and Deborah L. Santavy

Coral growth anomalies are changes in the coral cells that deposit the calcium carbonate skeleton. They usually appear as raised areas of the skeleton and tissue that are different from the surrounding normal areas on the same colony. The features include abnormal shape, size, and development or loss of the corallites (i.e., skeletal cups that protect the polyps), and either paler or darker tissue color. Because growth anomalies are well-circumscribed masses with a faster rate of skeletal accretion, they have been called tumors and compared to cancer. The causes are unknown, although recent research suggests an infectious agent, such as a virus or DNA mutations caused by ultraviolet light or toxins, might produce abnormal proliferating cells. Two kinds of growth anomalies are generally recognized.

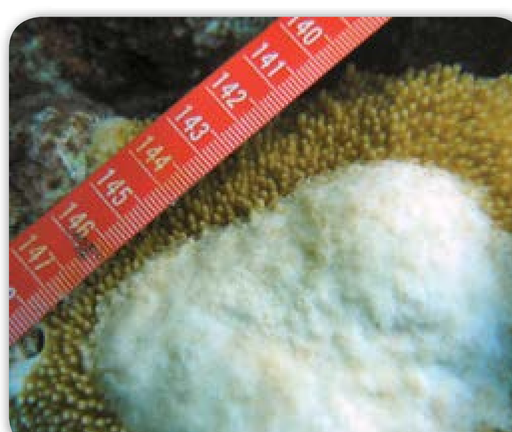
E.C. Peters - GMU

Gigantism. These lesions appear as bulging growths and have been found on reefs throughout the Florida Keys and worldwide. Gigantism results from rapid growth and multiplication of a single polyp, and the abnormal skeletal elements can be either larger than those on the rest of the colony or can consist of corallites that are smaller than those on the rest of the colony. The skeleton produced by the abnormal polyps often is less dense than the surrounding material.

E.C. Peters - GMU

Abnormal corallites can also be smaller than those on the rest of the colony, as seen on this lesion occurring on an elliptical star coral.

Neoplasia. Cells in these lesions produce only gastrovascular canals and skeleton. The lesions proliferate and connect all polyps, which disappear from the porous, whitened protuberant masses. Neoplastic lesions are found on acroporid corals, such as the elkhorn coral (*Acropora palmata*), and appear as "bubbly" translucent coral tissue at the lesion margin. Affected tissue lacks symbiotic algae, loses its mucus-secreting protective cells, does not produce eggs and sperm for reproduction, and can die. This growth anomaly is considered to be a coral cancer.



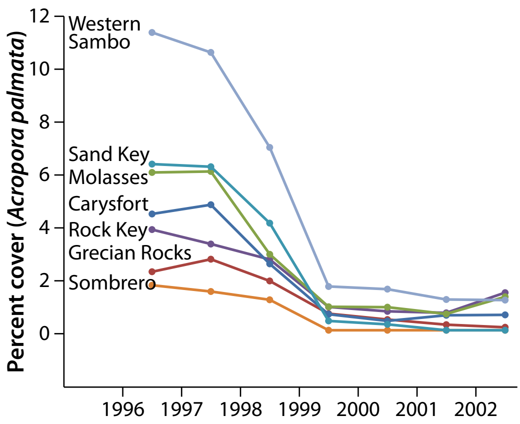
E.C. Peters - GMU

Close-up of a neoplastic lesion in elkhorn coral. Affected tissue lacks symbiotic algae and mucus-secreting cells and is protuberant. Scale is in centimeters.

Elkhorn corals are susceptible to white-pox disease

Kathryn Patterson Sutherland, Erin K. Lipp, and James W. Porter

In 1996, a new coral disease called white pox was first reported to affect elkhorn corals (*Acropora palmata*) at reefs near Key West. The disease was common on Florida reefs between 1996 – 2001, and during that time period, elkhorn coral populations declined by 87% Keys-wide. A second species of branching acroporid coral, the staghorn coral (*Acropora cervicornis*), also suffered significant declines in the mid- to late-1990s due to a similar disease called "white band."



Adapted from Sutherland and Ritchie (2004) with kind permission from Spring Science and Business Media

Percent cover of living elkhorn coral at reefs in the Florida Keys National Marine Sanctuary. Coral cover declined an average of 87% between 1996 – 2002.

White pox and white band are the most commonly reported diseases for the branching corals on Atlantic and Caribbean reefs. Between the 1970s – 1980s, white-band disease is believed to have resulted in a Caribbean-wide decline of branching corals. Although many of the populations of branching corals were lost due to a combination of white-band disease, bleaching, and hurricane damage in the Florida Keys, coverage remained at about 12% for elkhorn and staghorn corals during the mid-1990s when wide-scale observations of white-pox disease were first recorded and the percent coverage of elkhorn coral dropped to less than 2%.

Outbreaks of white-pox disease have been observed throughout the Caribbean, but the focus of the disease outbreak appeared to be in the Florida Keys. The decimation of the populations of branching corals in Florida contributed to the May 2006 listing of elkhorn and staghorn corals as threatened under the United States Endangered Species Act.

In 2002, a bacterium called *Serratia marcescens* was identified as a cause of white-pox disease. This bacterium is common in the intestines and feces of humans and other animals and in freshwater and soil. Recent studies recovered a unique strain of *S. marcescens* from diseased corals and sewage. The strain, isolated from reef and sewage sources, establishes a definitive connection between human sewage and white-pox disease of corals. These studies also demonstrate that *S. marcescens* cannot be isolated from all coral colonies apparently affected by white-pox disease. Outbreaks of white pox have waned in intensity since 2000, although the disease is still commonly reported. The current low prevalence of the disease may be due to the decimation of susceptible elkhorn populations during previous outbreaks and the loss of large colonies due to hurricanes. The observation of small recruits and isolated large colonies indicates that elkhorn corals that are resistant to white pox may exist.

J.W. Porter - UGA

Elkhorn coral affected by white-pox disease. White patches are denuded coral skeleton from which all living coral tissue has been lost.

Aspergillosis is a fungal disease that affects sea fans

Kiho Kim

In the Florida Keys, the sea fan coral, *Gorgonia ventalina*, is a common and iconic member of reef communities. The sea fan coral is made up of an intricate latticework of branches that form a large, flat fan that is usually oriented perpendicular to the dominant direction of water flow. In 1995, sea fans around the island of Saba (Netherlands Antilles) were found with unusual lesions, a sign of disease. By the summer of 1996, such lesions were also found on sea fans in the Florida Keys.

This disease, which has now spread throughout the Caribbean and affects all three species of Caribbean sea fans, leads to purpling of tissue surrounding the lesions and galls that may grow to 2 – 3 centimeters (0.8 – 1.2 inches) in diameter. The impact of aspergillosis on sea fans has been well documented in the Florida Keys. The first large-scale survey in 1997 revealed disease prevalence of nearly 43%; subsequent studies documented mortality rates ranging from 5% – 95% per year among infected sea fans. The disease tended to increase during the summer months and was the most severe among the larger sea fans. Once infected, there was near-complete reproductive failure, leading to low levels of recruitment during the outbreak. The disease began to decline in 2000, and by 2005 the disease prevalence was less than 1% throughout the Keys.

The disease is caused by the fungus *Aspergillus sydowii*. The pathogen was unexpected given it is a common soil fungus that was only occasionally isolated from aquatic environments. Moreover, although *Aspergillus* fungi in general are opportunistic pathogens, none were known previously to affect marine invertebrates. Thus, unanswered questions regarding this disease include "What triggered the outbreak in 1995?" and "How did the fungus evolve from a soil organism into a marine pathogen?" Scientists are still working on answering these questions.

Elevated temperature and nutrient pollution are likely stressors leading to the outbreak of aspergillosis in sea fans. Warmer water tends to favor the growth of the pathogen while stressing the coral. In addition, nitrogen pollution seems to increase the severity of the disease.

K. Kim - AU

Aspergillosis is a disease of sea fans caused by the common soil fungus, *Aspergillus sydowii*. Infection results in tissue necrosis surrounded by areas characterized by a deeply purple margin.

Scientists are learning that sea fans are capable of defending themselves by using a suite of chemical (e.g., anti-fungal compounds), cellular (e.g., immune response), and physical means. Activation of those defenses is marked by the purpling of disease-affected tissue. The purpling results from an increase in the proportion of purple sclerites (small carbonate skeletal elements) and indicates an attempt to fortify vulnerable coral tissue and reduce the spread of the pathogen. It should be noted that the purpling is a general response to contact with living agents, so care must be taken when diagnosing sea fans with aspergillosis.

Physical stressors affect the Southeast Florida Reef System

David S. Gilliam and Jocelyn L. Karazsia

The Florida reef system is extensive, running parallel to the coast for 500 kilometers (305 miles) from Martin County to the Dry Tortugas. The Southeast Florida Reef System extends for more than 150 km (91.5 mi) from Martin County to Miami-Dade County. There are over 30 species of stony corals living on the high-latitude reef system. They comprise 2% – 3% of the reef cover that includes a diverse assemblage of gorgonians, sponges, and fishes. The Southeast Florida Reef System includes unique areas with higher stony coral cover (greater than 10%), including significant populations of the staghorn coral (*Acropora cervicornis*).

The Southeast Florida Reef System lies within 4.5 km (3 mi) of a coast that is home to more than 6 million people. The proximity to a highly populated urban area subjects the reef system to ever-increasing physical stressors (impacts). Physical stressors are perhaps a greater threat to the Southeast Florida Reef System than they are to the rest of the Florida reef system. Physical threats include anchoring and gear impacts associated with commercial and recreational fishing and diving; sewage outfalls; marine construction activities, such as fiber optic cables; beach renourishment; channel dredging; and major shipping ports and ship groundings.

Physical stresses to the Southeast Florida Reef System have historically included damage to the reef framework (e.g., fracturing, breaking, crushing) as well as injuries to the reef community (e.g., dislodged, overturned, and fragmented sponges, octocorals, and stony coral colonies). These injuries result in a loss of biological and physical resources, which disrupts normal coral reef ecosystem function. These detrimental effects extend beyond the actual injured reef habitat to numerous reef-associated and reef-dependent species that utilize the reef for shelter and feeding.

Southeast Florida has nine inlets and three major ports: Port of Palm Beach in Palm Beach County, Port Everglades (Fort Lauderdale) in Broward County, and the Port of Miami in Miami-Dade County. At Port Everglades alone, over 5300 ships call annually. Inlets and ports require periodic maintenance dredging to keep them navigable. Generally, maintenance dredging does not directly impact reef communities but may indirectly stress

D.S. Gilliam - NSU

Fragmented and overturned brain corals from a ship grounding at a southeast Florida reef. Reconfiguration of anchorages at Port Everglades and the Port of Miami will reduce the likelihood of future groundings. Restoration activities are required to reverse physical impacts to reefs.

these communities through increased turbidity and sedimentation. Turbidity occurs when sediments are suspended in the water column and can clog fish gills, lessen feeding efficiency, and reduce the amount of light available to light-dependent organisms, such as corals. Sediment deposition can result in reef burial. Port expansion projects can have a direct impact on many hectares of coral habitat through dredging for the widening and deepening of entrance channels. The Port of Miami entrance channel has recently been approved for deepening and widening, and expansion projects are proposed for Port Everglades and Port of Palm Beach. The anchorages associated with the ports can also pose a significant threat to the Southeast Florida Reef System. Ships use anchorages while waiting for berths, travel orders, or good weather for travel. Unfortunately, these anchorages are currently located very close to or on coral habitat, and the areas adjacent to anchorages are much more likely to be affected by anchor drags and major grounding events by large ships.

Since 1994, over 10 major ship groundings have been documented near Port Everglades, damaging in total more than 5 hectares (12 acres) of reef habitat. Reattachment of fragmented and dislodged stony coral colonies was completed after many of the grounding events, but reef recovery is very slow, and full recovery, if possible, may require tens to hundreds of years.

A. Booher - FEMA

Beach nourishment is performed to replace sand lost to erosion. Sand is pumped from offshore sites to the beach. Impacts to nearshore hardbottom areas by placement of sand have been documented, and offshore reefs may be impacted by turbidity associated with sand dredging.

There is some good news. With the combined efforts of concerned local, state, and federal agencies and academia, the Port Everglades anchorage has been reconfigured by eliminating the shallower anchorage, which was located between reefs, and expanding the deeper outer anchorage (Federal Register/Vol. 73, No. 24/Tuesday, February 5, 2008/Rules and Regulations). These changes will greatly reduce the likelihood of future groundings. Efforts are underway to reconfigure the Port of Miami anchorage to reduce impacts to reefs in that area.

Beaches are important to the economy of southeast Florida, but because of changing environmental conditions, storms, and inlets that disrupt natural sand movement, many southeast Florida beaches undergo periodic beach nourishment. Generally, sand is dredged from offshore locations (borrow pits) located between the reef terraces, and pumped onto beaches. Projects are designed to minimize impacts to hardbottom areas close to the beach and avoid impacts to offshore reefs near the borrow pits. However, beach dredge-and-fill activities can bury nearshore hardbottom reef communities, and offshore reef communities may be directly affected by dredging too close to the reefs or by increased turbidity and sedimentation from the sand excavation activities. Although monitoring is conducted before, during, and after these projects, the long-term and cumulative impacts from repeated nourishment activities are unknown.

Although smaller in scale, other coastal construction activities that have physically impacted the Southeast Florida Reef System include the installation of fiber optic cables and geotechnical boring (i.e., drilling) for possible placement of natural gas pipelines. Individually, these activities generally affect small areas, but cumulative impacts associated with numerous projects along the entire southeast Florida coast can have significant effects on the reef system.

The southeast Florida population is likely to continue to grow, and the physical stressors associated with this growth are going to increase. Management agencies responsible for protecting and conserving the reef system must continue to require avoidance and minimization of physical impacts for all coastal construction activities that have the potential to harm reef communities. A better understanding of reef recovery rates will support resource management decisions that result in reduced impacts. Increased public awareness of the Southeast Florida Reef System will prompt decision makers to eliminate, or at least reduce, physical stresses on the system.

Biological stressors affect south Florida coral reefs

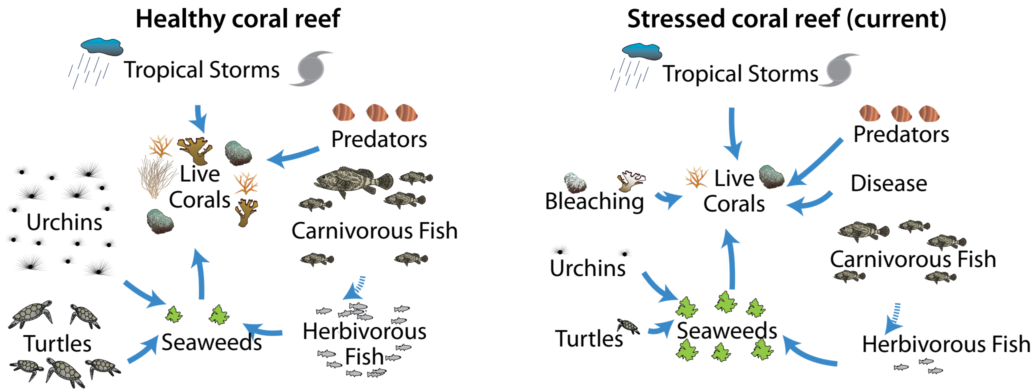
Margaret W. Miller

Coral reefs are the sum of the presence, abundance, and function of their parts. The status of a coral reef ecosystem is defined by what organisms are present, how many of them are there, and what they are doing. Also, it is important to know how reef organisms "make a living" (i.e., what they eat and what eats them).

Because reefs are diverse ecosystems, there are also lots of ways that the different players interact. Some interactions are beneficial, and some are not. For example, there are a range of reef organisms (from worms to snails to fish) that eat live coral tissue. These coral predators can have very detrimental impacts, especially when predators become abundant or corals become rare because of mortality from other stressors. These coral predators may themselves be preyed upon by higher predators, and so reduction in the numbers of higher predators may result in higher predation on corals.

Fishing has radically changed south Florida reef communities. Most targeted fish populations, such as large grouper and snapper species and lobster and queen conch, have been reduced to very low population levels. Most of these targeted species are predators, and it is likely that removing such a large volume of predators affects the entire ecosystem by allowing their prey to proliferate. Because the coral reef ecosystem is so complex, the exact nature and extent of these effects are difficult to quantify.

Coral reefs are somewhat different from many ecosystems in that they normally contain a relatively low abundance of living plant matter (relative to forests, grasslands, seagrass meadows, or kelp beds). This is largely because almost all of the plant growth is immediately eaten by reef grazers. Indeed, one of the major changes observed throughout the world when coral reefs are degraded is a proliferation of reef seaweeds. This can result from increased resources for the plants (e.g., influx of nutrients from human sources such as sewage or fertilizer runoff), which allow them to grow faster, or from a reduction in the grazing level that slows their removal, such as the Caribbean-wide die-off of grazing sea urchins. When seaweeds proliferate on reefs, they occupy space that then is not available to corals or other benthic animals for recolonization. Also, some seaweeds may exude chemicals or trap sediments that are harmful to adult and, especially, juvenile corals.



A healthy coral reef ecosystem (left) and a biologically stressed coral reef ecosystem (right). Arrows indicate consumption or other negative impact to live corals. Urchins and turtles have been drastically reduced on present-day reefs. Loss of herbivory resulted in increased amounts of seaweeds that compete with corals for space.

Reefs of the past: Key Largo Limestone lacks branching coral species

William F. Precht , Lindsey L. Precht, and Steven L. Miller

Key Largo Limestone forms the present-day islands of the Upper and Middle Florida Keys. These coral-rich limestones were formed during the last interglacial high sea-level stand that occurred in the Pleistocene Epoch between 120,000 – 135,000 years ago. Key Largo Limestone has been well studied, and it has been noted that all the coral species identified in the Key Largo Limestone are living today in the waters of the Florida Keys Reef Tract. However, not all of the corals living today have been found in the Key Largo Limestone. All descriptions of Key Largo Limestone note the presence of a coral assemblage dominated by massive boulder corals, an almost complete absence of elkhorn coral (*Acropora palmata*), a reef crest species, and a paucity of staghorn coral (*Acropora cervicornis*). What precluded the growth of these branching acroporid corals in south Florida during the Pleistocene Epoch?

The fact that coral reefs of south Florida are at the latitudinal extreme of reef development in the western Atlantic is one explanation for the lack of elkhorn coral in the Key Largo Limestone. The geographic range of a species contracts and expands in response to changing environmental conditions through time and space. At the apex of the last major interglacial period, the entire south Florida peninsula was flooded, creating a broad, shallow carbonate platform that allowed unimpeded flow from a much-enlarged Gulf of Mexico over a broad, shallow carbonate bank in the west to the Florida Straits and the open Atlantic in the east. Reef communities forming at the interface between the two waterbodies would have been bathed by waters of variable quality, temperature, salinity, and sediments. With no exposed islands (Keys) to protect the reefs during the winter months, chilled and sediment-laden Gulf waters would have periodically poured


W.F. Precht - FKNMS

Elkhorn corals presently grow in the Florida Keys, but are rarely found in Key Largo Limestone fossils from the Pleistocene Epoch (120,000 – 135,000 years before present).

onto these shelf-margin reefs. Under this scenario, the resulting coral community would have been essentially devoid of shallow, warm water-loving, reef crest species, such as elkhorn coral.

At slightly deeper depths on the fore reef, ephemeral thickets of fast-growing staghorn coral may have existed in sheltered pockets in an assemblage of boulder corals. This explanation is supported by an examination of growth bands in the fossilized coral skeletons of these species. Fossilized coral found in Key Largo Limestone had significantly reduced growth rates compared to growth under ideal conditions. This indicates that corals grew under fluctuating and hostile environmental conditions that were unfavorable to all but the hardiest reef-building coral species in Florida during the last major interglacial period. This same condition occurs today on a smaller scale, resulting in poorer coral reef growth conditions opposite tidal passes in the Middle Keys compared with areas in the lee of the island landmasses.

The last interglacial period has been proposed as a possible analog for future climate change and rapidly changing sea levels. Thus, understanding the presence and absence of individual species of reef corals in the Key Largo Limestone as a result of the changing environmental conditions during the Pleistocene Epoch, may hold the key to predicting the future of corals and coral reefs in the rapidly changing world.

Reefs of the future: a look into a crystal ball

Steven L. Miller and William F. Precht

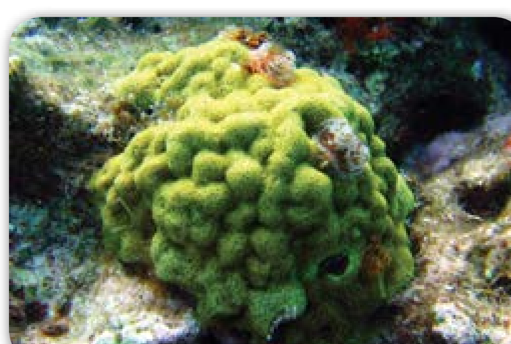
The long-term implications of coral reef decline experienced in Florida today are not known for certain, but it is likely that the current dramatic loss of corals could persist for decades or longer. Against the background of previous coral loss and the likelihood of continued decline, what would be required for natural coral reef recovery to occur in the Florida Keys? What will reefs of the future look like?

W.F. Precht - FKNMS

Elkhorn coral was prominent on reef crests in the recent past but was absent in reefs that formed the Florida Keys during the Pleistocene Epoch. It is possible that elkhorn and staghorn corals could repopulate reefs in the near future because they are fast-growing species, and remnant populations still exist. However, they are susceptible to epidemic coral diseases that could keep population numbers low unless disease-resistant strains prosper. In the long-term, sea-level rise could connect the Gulf of Mexico and Atlantic and result in conditions unfavorable for branching corals.

The most likely scenario in the short-term would be the recovery of populations of two ecologically and geologically important fast-growing species, elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*). Individual branches of both of these species can grow as fast as 10 centimeters (4 inches) per year, and with repeated branching that occurs annually, growth becomes geometric, which is sufficient to substantially repopulate all of the habitats previously occupied in Florida in a matter of decades. This is not an unreasonable expectation considering a recent estimate of over 10 million individual colonies of branching corals that are presently scattered across reefs and hardbottoms in the Keys. However, prolific and expansive thickets would be expected to grow only in the lee of large islands or seaward of the mainland of the Florida peninsula in areas protected from inimical waters of Florida Bay. If climate change is realized as predicted, a northward expansion of the branching corals and the reef tract could also be possible, mimicking conditions of the mid-Holocene warm period approximately 6000 years ago when coral reef growth was prolific as far north as Broward County.

C. Kendall - SEPM



F. Charpin - reefguide.org

Suitable lack of substrate, including proliferation of fleshy algae, may limit larval recruitment to reefs of the future (top). If conditions are not right for branching corals, "weedy" and brooding corals, such as mustard hill coral, may dominate reefs of the future (bottom).

What could prevent recovery of reefs dominated by branching corals? Disease pathogens are still present, cold weather fronts still occur, global warming and bleaching events are increasing in frequency and intensity, hurricanes can set back reef development, and predators are continuing to take their toll on remnant populations. The lack of suitable substrate may also limit larval recruitment of corals in areas where algal populations remain high. If one or both of the *Acropora* species do not recover, the continued high abundance of fleshy macroalgae and an increasingly important role for "weedy" and brooding corals, such as *Porites* and *Agaricia*, is likely. At longer time scales (decades to centuries), slower-growing, disturbance-tolerant, boulder coral species will most likely prevail.

Sea-level rise and the future of coral reefs in Florida

A challenge posed by global climate change is anticipating the potential response of the Florida Keys Reef Tract to the predicted levels of sea-level rise over the next few centuries. No matter what the ultimate rate or maximum level of sea-level rise may be, one thing is certain: the progressive flooding of the south Florida Platform will have serious consequences for reef development in the future. Specifically, predictions of future sea level superimposed on topographic charts for the Florida Keys has revealed that tidal passes will get larger between the Keys, and eventually, the entire island tract will be submerged. Most of the Florida Keys will flood with a rise of as little as 1 – 2 meters (3.3 – 6.6 feet) and would become totally submerged with a rise of little more than 5 m (16.4 ft). The result of this flooding would be unimpeded water flow between the Gulf of Mexico and the Atlantic that would continuously expose remaining reefs to waters of extreme variability in temperature, nutrients, salinity, and turbidity. These conditions would be especially hostile to temperature-sensitive species and would likely result in a coral community devoid of branching corals. In short, the present reef tract would drown, but in time, a new reef system would backstep and colonize the topographic highs on the platform. Using the past as a key to predicting the future, under optimum conditions, the resulting coral reefs and species would probably resemble the fossil coral reefs found in the Key Largo Limestone that lacks branching corals.

C. Kendall - SEPM

It is possible that reefs of the future may resemble the coral reefs formed in the Pleistocene Epoch and fossilized in the Key Largo Limestone. Elkhorn coral was almost completely absent from Pleistocene reefs probably because water quality conditions were not conducive to its growth or survival. This cross section of Key Largo Limestone shows a fossilized boulder coral.

Corals can be cultured and used for research and reef restoration projects

Diego Lirman

The recent patterns of widespread decline in coral abundance and condition have highlighted the need to promote localized activities to protect and recover surviving coral populations. In southeast Florida, the need for reef restoration is being addressed through the development of several coral nursery programs designed to salvage and propagate corals as well as through transplanting colonies to depleted or damaged habitats. Coral reef restoration using nursery corals has the potential to diminish or reverse population declines and accelerate the regrowth of a reef after chronic or acute disturbances. These programs, consisting of both in-water and land-based coral nurseries, are designed to provide a mechanism for salvaging corals that have been damaged by physical impacts such as ship groundings, or those that would be destroyed due to construction or dredging projects. After collection and transportation to the nurseries, parent colonies are propagated through controlled fragmentation, thus continuously increasing the available stock.

With funding from The Nature Conservancy and the National Oceanic and Atmospheric Administration Coral Reef Conservation Program, in-water coral nurseries dedicated mainly to the study and propagation of the branching corals staghorn (*Acropora cervicornis*) and elkhorn (*Acropora palmata*) have been established in southeast Florida. In-water coral nurseries are presently located in Broward County (managed by Nova Southeastern University), Biscayne National Park (managed by the National Park Service and the University of Miami), the Upper Florida Keys (managed by Ken Nedimyer), and the Lower Florida Keys (managed by Mote Marine Laboratory). Land-based nurseries are found at the University of Miami and Mote Marine Laboratory. Additional coral nurseries are planned in the near future for both the Florida Keys and the Dry Tortugas.

D. Lirman - UM RSMAS

Platform used to grow staghorn fragments in Florida nurseries prior to transplantation back to the reef.

The goals of this program are to develop effective coral fragmentation and propagation methodologies and to evaluate the role of genetics on coral resilience. The fast growth of staghorn and elkhorn corals, up to 10 centimeters (4 inches) per year, makes them ideal candidates for propagation and restoration programs. Once among the most abundant, elkhorn and staghorn corals have experienced a drastic decline mainly due to hurricane impacts, elevated temperatures, and coral diseases. This regionwide decline has resulted in losses of up to 95% of colonies at many locations. It is expected that the staghorn and elkhorn coral fragments kept in the Florida nurseries will provide an expanding coral stock to be used in future reef restoration and scientific experiments.

Nursery-grown corals provide reef scientists with coral microcolonies of known genetic makeup. Scientists can use these corals in controlled laboratory experiments on coral physiology and other topics, such as coral diseases and the impacts of global climate change on coral calcification and growth.

Coral propagation can produce large numbers of coral transplants

David Vaughan and Erich Bartels

Historically, coral reef restoration programs were initiated primarily in response to physical impacts from vessel groundings and anchor damage. Restoration efforts generally included stabilization of the substrate and reattachment of damaged corals. More recently, the widespread loss of stony corals due to increasing sea surface temperatures, coral bleaching and diseases, and other stressors and disturbances has increased at such an alarming rate that other restoration techniques are being explored. One such alternative is the cultivation and propagation of live corals in coral nurseries.

E. Bartels - MML

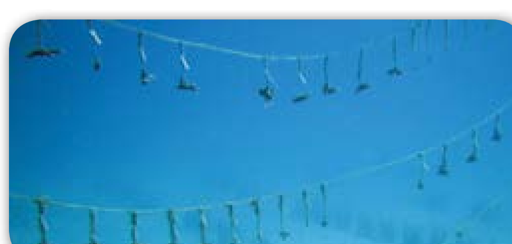
Newly mounted staghorn coral fragment epoxied onto cement culture base. Coral fragment is about 2.5 centimeter (1 inch) long.

Establishing and maintaining a coral nursery, either land-based in large tanks or field-based (*in situ*), entails propagating corals through the use of small pieces called fragments that are attached to artificial substrate. In order to establish a brood-stock population, small coral fragments are acquired from nearby stocks of healthy corals or from colonies fragmented by storms or other impacts. Various methods have been used for stabilizing and growing these small fragments, including mounting to concrete disks, suspending them from frames or racks secured to the bottom, and hanging them from lines suspended off the seafloor.

E. Bartels - MML

Nursery-grown staghorn coral colony.

After 1 – 2 months, coral polyps begin to overgrow the material they are attached to, and after 6 – 12 months, a fragment of staghorn coral (*Acropora cervicornis*) can more than double in size and produce three or more branching sections. This brood stock coral can then be further fragmented to produce multiple replicate fragments for continued culture in the nursery, or the cultured coral can be outplanted at a restoration site by attaching the entire coral to the substrate. Using these methods, coral nurseries can produce large numbers of coral transplants in a relatively short period of time using a minimal amount of natural material as brood stock. As a result, nursery-based cultivation of corals is likely to become an important resource for the restoration and stabilization of coral populations on south Florida reefs.



E. Bartels - MML

In situ staghorn coral nursery. Corals are grown on concrete blocks and suspended on lines in the water column.

The Coral Rescue and Nursery Program benefits restoration, research, aquaculture, and aquaria

Lauri MacLaughlin

The Florida Keys National Marine Sanctuary (FKNMS) Coral Rescue and Nursery Program relocates coral colonies that are threatened by unavoidable coastal development activities and maintains the rescued corals for use in restoration and science projects. Examples of threats to corals rescued by this program include seawall construction and repairs, marina and dock development, and shoreline stabilization projects.

L. MacLaughlin - FKNMS

Typical encrusting coral at Truman Mole Pier, Key West being removed using hand tools.

Corals are carefully removed from their substrate using hand tools. The rescue program began during the repairs of the Key West Truman Harbor Mole Pier in 2003 when thousands of healthy corals attached to the existing pier walls were in peril. FKNMS staff have developed protocols for coral risk assessment, rescue, and transplantation, and provides training for private contractors, agency personnel, and volunteers working on such projects within the Sanctuary. The Sanctuary partners with public and private aquaria, universities, research laboratories, state and national parks, local residents, and students to help salvage threatened corals.

Rescued corals are maintained in a coral nursery located at the Nancy Foster Florida Keys Environmental Complex in Key West, Florida. Corals are kept until they can be placed in FKNMS-approved beneficial use projects.

Currently, approximately 350 individual pieces of stony corals, representing 14 genera, are being cared for and are awaiting relocation. Rescued corals are transferred to appropriate education, research, aquaculture, and restoration projects. Use of rescued corals for projects relieves collecting pressure from natural habitats by providing scientists with an alternate and viable source of coral samples. Results of research with rescued corals provides a scientific basis for effective management to help protect coral reefs, including identifying factors contributing to reef resilience to bleaching and other diseases.

L. MacLaughlin - FKNMS

Rescued corals are maintained in baskets in Truman Harbor, Key West.

Florida has an active artificial reef program

Jon Dodrill and Pamela J. Fletcher

Artificial reefs are materials intentionally placed on the seafloor by humans to accomplish specific biological and/or socioeconomic objectives. In south Florida, artificial reefs consist of humanmade materials, such as "clean" designed or precast concrete structures, building rubble, and steel vessels and barges, as well as natural substances, such as limestone. Artificial reefs may be used to mitigate losses or damage to natural reef systems caused by vessel groundings or other impacts. They may also be used as habitat enhancements to provide substrate for shellfish, corals, and other benthic organisms and as shelter for dozens of fish species that use the reefs in the course of their individual life cycles for shelter, feeding, or breeding.

K. Millie - FWC

South Florida has an active artificial reef program that includes the deployment of steel vessels, such as the Governor's Reef located in Palm Beach County.

Florida has one of the most active artificial reef programs in the nation. There are approximately 705 artificial reefs along the south Florida coastline from Martin County to Lee County. These are placed at nearshore or estuarine bay or lagoonal sites (i.e., Lake Worth Lagoon, Palm Beach County) at depths as shallow as 3.6 meters (12 feet) and at offshore locations as deep as 91.4 m (300 ft). Each artificial reef is strategically placed on the ocean floor within approved reef sites permitted by the U.S. Army Corps of Engineers and the Florida Department of Environmental Protection. In south Florida, there are no private reef deployments, and projects are overseen by local government resource managers. Projects must comply with permit conditions and adhere to guidelines established by the Florida Fish and Wildlife Conservation Commission. The site and the materials deployed must be inspected to ensure the reefs remain where placed, do not harm the marine environment, and do not become an obstruction to navigation.

Why construct artificial reefs?

Artificial reefs have been constructed with one or more of the following intended objectives:

1. Enhance private recreational and charter fishing and diving opportunities;
2. Provide a socioeconomic benefit to local coastal communities;
3. Increase reef fish habitat;
4. Reduce user conflict;
5. Facilitate reef-related research;
6. Provide for mitigation or restoration of damaged hardbottom; and
7. While accomplishing objectives 1– 6, do no harm to benthic communities, fishery resources, Essential Fish Habitat, or human health.

Structures placed on the seafloor for engineering purposes to manipulate shoreline processes (e.g., wave attenuation devices, jetties, erosion control structures), as well as accidental shipwrecks or other materials lost at sea, are not classified as artificial reefs under the Florida Fish and Wildlife Conservation Commission definition of artificial reefs.

Artificial reefs have economic value

Grace M. Johns

Artificial reefs are humanmade habitats built from various materials, including rock, old ships, concrete, and prefabricated modules. They are placed in areas away from natural reefs, creating new marine life communities.

D.S. Gilliam - NSU

Tetrahedrons are commercial modules that are used to create artificial reefs. Tetrahedrons stack in a stable configuration and offer multiple-size interstices for reef dwellers.

Over the past several decades, both nearshore and offshore habitats for many fish and shellfish have been significantly reduced or heavily impacted by coastal development, accidents, and severe storms. The reduction of these habitats, along with increased pressures on our remaining coastal resources, has led to declines in many marine life populations.

County	Residents	Visitors	Total
Martin	143,000	117,000	260,000
Palm Beach	1,075,000	330,000	1,405,000
Broward	1,281,000	2,690,000	3,971,000
Miami-Dade	1,540,000	1,410,000	2,950,000
Monroe	1,102,000	480,000	1,582,000
Total	5,141,000	5,027,000	10,168,000

Approximately 10.2 million person-days were spent recreating on artificial reefs in southeast Florida in 2001. This is about one half as many days as are spent recreating on natural coral reefs.

County	Fishing	Snorkeling	SCUBA	Total
Martin	241,000	6,000	13,000	260,000
Palm Beach	613,000	327,000	465,000	1,405,000
Broward	1,866,000	249,000	1,845,000	3,960,000
Miami-Dade	1,939,000	625,000	385,000	2,949,000
Monroe	800,000	398,000	379,000	1,577,000
Total	5,459,000	1,605,000	3,087,000	10,151,000

Number of person-days spent recreating on southeast Florida artificial reefs in 2001. Overall, fishing and SCUBA diving are the predominant activities on artificial reefs. (Data do not include glass-bottom boat tours.)

Artificial reefs provide food, shelter, protection, and spawning areas for hundreds of species of fish and other marine organisms. They also provide alternate areas for use by SCUBA divers and anglers, reducing the user pressures on natural reefs. Palm Beach County and Broward County have a significant number of artificial reefs, and more are constructed every year. However, they are not a panacea, and additional research is required to quantify their use in fisheries management. They have been used to offset losses of nearshore reefs to beach nourishment projects, but the value of replacement of inshore fish refuges with artificial structures requires more research.

County	Dollars spent	Pay to protect	Total value
Martin	$10	$4	$14
Palm Beach	117	9	126
Broward	587	56	643
Miami-Dade	277	10	288
Monroe	123	10	132
Total	$1,114	$89	$1,203

Recreators spent $1.1 billion to use artificial reefs in 2001 and were willing to pay an estimated additional $89 million to protect them. Thus, their total annual value to recreators is $1.2 billion. (Data are in millions of dollars.)

You can help to protect Florida coral reefs

Brian D. Keller

Even if you do not live near a coral reef, you can help to protect them. Effects of global warming and physical damage by careless actions are major threats to coral reefs of the world.

Things you can do to combat climate change:

- Reduce the amount of fossil fuels that you consume by improving the energy efficiency of your home and business.
- Reduce driving by selecting energy-efficient vehicles, carpooling, walking, and bicycling.
- Support efforts of local, state, and national governments and private industries to reduce the amount of fossil fuel consumption.

NOAA

Anchoring on coral reefs causes physical damage to corals and other reef organisms. Please use mooring buoys.

Actions you can take to avoid direct impacts to coral reef resource:

- Do not anchor on reefs. Use mooring buoys when available.
- Do not touch corals when diving or snorkeling. Keep fins, gear, and hands away from the reef to avoid damage to delicate corals.
- Stay off the bottom because disturbed sediments can smother corals.
- Use approved marine sanitation devices and onshore pump-out facilities to dispose of wastewater.
- Do not throw trash into the water.

Other things you can do to conserve coral reef resources for the enjoyment of future generations:

- Educate yourself and others about coral reefs and the creatures that they support.
- Support organizations that protect coral reefs.
- Volunteer for a reef cleanup activity
- Participate in the Great Annual Fish Count.
- Be an informed consumer. Buy marine fish and other organisms that have been collected in an ecologically sound manner.
- Buy products that are coral inspired rather than coral derived.
- Support reef-friendly businesses, including dive shops, marinas, hotels, and other coastal businesses.
- Hire local guides when visiting coral reefs.
- Recycle trash to keep it out of oceans and landfills.
- Conserve water so there is less runoff and wastewater that can get back into marine environments.
- Report dumping or other illegal activities to enforcement agencies. Be the eyes and ears of the reef!
- Support local efforts to improve wastewater and stormwater treatment and disposal methods.

NOAA

Coral reefs and their organisms, such as these gray snappers, are susceptable to impacts of climate change. Do your part to reduce greenhouse gases.

Introduction citations

1. National Oceanic and Atmospheric Administration. What are Coral Reefs? NOAA's Coral Reef Information System. Available from: http://coris.noaa.gov/about/what_are/(Updated 2 Dec 2010; cited 16 Feb 2011). *General information about corals and coral reefs.*
2. Florida Fish and Wildlife Conservation Commission. Fish and Wildlife Research Institute. What are Corals? Available from: http://research.myfwc.com/features/view_article.asp?id=32399 (Cited 16 Feb 2011). *Differences between hard corals and soft corals and differences between coral habitats. Includes link to Annual Report of the Coral Reef Evaluation and Monitoring Program.*
3. National Oceanic and Atmospheric Administration. Corals. NOAA Ocean Service Education. Available from: http://oceanservice.noaa.gov/education/tutorial_corals/welcome.html (Updated 11 Dec 2009; cited 16 Feb 2011). *Coral tutorial: What are corals? How do they grow? Relationship between corals and zooxanthellae. Importance of reefs, threats to reefs, and coral diseases.*
4. Wikipedia. Coral. Available from: http://en.wikipedia.org/wiki/Coral (Updated 9 Feb 2011; cited 16 Feb 2011). *Summary of coral taxonomy, structure, reproduction, and threats.*
5. Youle M. 2009. What are corals, really? The Reef Tank. Available from: http://www.thereeftank.com/blog/corals/ (Cited 16 Feb 2011). *Linnaeus misclassified corals as Zoophyta (animal plants). Importance of zooxanthellae.*
6. National Oceanic and Atmospheric Administration. Zooxanthellae...What's that? NOAA Ocean Service Education. Available from: http://oceanservice.noaa.gov/education/tutorial_corals/coral02_zooxanthellae.html (Updated 9 Apr 2010; cited 16 Feb 2011). *Association of corals and symbiotic algae (zooxanthellae).*
7. Coral Reef Alliance. 2010. Coral Reef Overview, The Basics. Available from: http://www.coral.org/resources/about_coral_reefs/coral_overview (Cited 16 Feb 2011). *Tutorial on corals and coral reefs including age of coral reefs, growth rates, reproduction.*
8. Wikipedia. Coral Reef. Available from: http://en.wikipedia.org/wiki/Coral_reef (Updated 16 Feb 2011; cited 16 Feb 2011). *Where are coral reefs found and how do they grow?*
9. Jaap WC, Hallock P. 1990. Coral reefs. In: Myers RL, Ewel JJ (eds.). Ecosystems of Florida. Orlando, FL: Univ. Central Florida Press. p. 574-616. *Types of reefs, where they are found, growth rates, nutrient cycling, reef management.*
10. Jaap WC. 1984. The Ecology of South Florida Coral Reefs: A Community Profile. U.S. Fish Wildl. Ser. Off. Biol. Ser. Tech. Rep. FWS/OBS 82-108. *Coral reef types and distribution, formation, biology, threats.*
11. Hallock P. 1997. Reefs and reef limestones in Earth history. In: Birkeland C (ed.). Life and Death of Coral Reefs. New York: Chapman and Hall. p. 13-42. *A history of coral reef development.*
12. National Undersea Research Center, University of North Carolina at Wilmington, National Oceanic and Atmospheric Administration, National Aeronautics and Space Administration, College of Charleston Project Oceanica. Oculina Coral Banks 2002. Available from: http://oceanica.cofc.edu/oculina/home.htm (Cited 16 Feb 2011). *Survey of Oculina banks off Florida's east coast.*
13. Marszalek DS, Babashoff Jr G, Noel MR, Worsley DR. 1977. Reef distribution in south Florida. Proc. Third Int. Coral Reef Symp. 223-229. *Summary of reef types and their distribution in south Florida.*
14. Roberts HH, Wilson PA, Lugo-Fernandez A. 1992. Biologic and geologic responses to physical processes: examples from modern reef systems of the Caribbean-Atlantic region. Cont Shelf Res. 12:809-834. *Orientation of spur-and-groove formation reflects direction of waves.*
15. University of Puerto Rico, Department of Geology. Reef Character- Morphology of Caribbean Reefs. Available from: http://geology.uprm.edu/Morelock/rfcharact.htm (Cited 16 Feb 2011). *Influence of strong wave surge on elkhorn coral (*Acropora palmata*) forms spur-and-groove systems.*
16. Haynes AR, Floyd LS. 2008. Coral recruitment and community development: The Broward County artificial reef compared to adjacent hardbottom areas, five years post-deployment. Proc. 11th Int. Coral Reef Symp. 1240-1243. *Quantitative study on the fauna on an artificial reef.*
17. World Wildlife Fund. Coral Reefs. Available from: http://www.panda.org/about_our_earth/blue_planet/coasts/coral_reefs/ (Cited 17 Feb 2011). *Coral reefs are home to about 25% of marine life. Threats to coral reefs.*
18. Deep Sea Waters. Coral Reefs. Available from: http://www.deepseawaters.com/coral.htm (Cited 17 Feb 2011). *One-third of all marine fish species live on coral reefs, and a summary of threats to coral reefs.*
19. Wikipedia. Coral reef fish. Available from: http://en.wikipedia.org/wiki/Coral_reef_fish (Cited 17 Feb 2011). *As many as 6000 to 8000 fish species are found on the world's coral reef ecosystems.*
20. Goli R. 2009. Coral Reefs-The Rainforests of the Sea: How coral reefs remain one of the most diverse ecosystems on earth. Suite 101.com. Available from: http://www.suite101.com/content/coral-reefs-the-rainforests-of-the-sea-a134248 (Cited 17 Feb 2011). *Biodiversity of coral reefs can be compared to tropical rainforests.*
21. Shah A. 1998. Biodiversity. Global Issues. Available from: http://www.globalissues.org/issue/169/biodiversity (Updated 16 Jan 2011; cited 17 Feb 2011). *Importance of maintenance of global biodiversity.*
22. Mac Gillivray Freeman Films. 2003. Coral Reef Adventure: About Corals and Coral Reefs. Available from: http://www.coralfilm.com/about.html (Cited 17 Feb 2011). *Primer on coral biology, how corals grow, threats to coral reefs, benefits of corals to society, and what citizens can do to protect corals.*
23. Thurman HV, Burton EA. 1995-2010. Introduction to Oceanography. Chapter 21: Issue 2- Coral Rocks! The Value of the World's Coral Reefs. Available from: http://wps.prenhall.com/esm_thurman_introocean_9/5/1359/348040.cw/index.html (Cited 17 Feb 2011). *Importance of corals in global carbon cycle.*
24. Johns GM, Leeworthy VR, Bell FW, Bonn MA. 2001. Socioeconomic Study of Reefs in Southeast Florida. Hazen and Sawyer, Florida State University, and National Oceanic and Atmospheric Administration. Available from: http://marineeconomics.noaa.gov/reefs/02-01.pdf (Cited 17 Feb 2011). *An analysis of reef use, socioeconomic characteristics of reef users, and economic contribution of natural and artificial reefs in southeast Florida.*
25. Fonseca CE. 2009. The value of Fijian coral reefs by nonusers: A contingent valuation study to investigate willingness-to-Pay for conservation, understand scale/magnitude of reef problems and provide tools for practitioners. Ph.D. Dissertation, Georgia Institute of Technology, 251 pp. Available from UMI ProQuest Dissertations and Theses: http://gradworks.umi.com/33/76/3376277.html (Cited 17 Feb 2011). *The results of this study demonstrate that Atlanta residents, who are located very far from Fiji, are willing to contribute to Fijian coral reef conservation programs.*
26. The Nature Conservancy. 2010. Resource managers

launch response to coral bleaching in wake of cold snap. TNC News Room. Available from: http://www.nature.org/pressroom/press/press4368.html?src=rss (Cited 17 Feb 2011). *Cold weather in January 2010 killed corals in the Florida Keys.*

27. Precht WF, Miller SL. 2007. Ecological shifts along the Florida Reef Tract: The past as a key to the future. In: Aronson RB (ed.). Geological Approaches to Coral Reef Ecology. New York: Springer. p. 237-312. *Water exiting tidal passes from Florida Bay is inimical to coral growth and reef development.*
28. Anthony KRN, Connolly SR. 2004. Environmental limits to growth: physiological niche boundaries of corals along turbidity-light gradients. Oecologia 141(3):373-384. *Energy costs to corals in varying light and turbidity regimes are species specific.*
29. Public Library of Science. 2010. Distressed Damsels Stress Coral Reefs. Science Daily. Available from: http://www.sciencedaily.com/releases/2010/05/100527013236.htm (Cited 17 Feb 2011). *Three-spot damsel fish are killing weakened corals.*
30. National Oceanic and Atmospheric Administration, National Ocean Service. Lost lobster traps have big impact in the Florida Keys. Available from: http://oceanservice.noaa.gov/news/weeklynews/dec08/lobstertraps.html (Updated 19 Dec 2008; cited 17 Feb 2011). *Derelict lobster traps can trap, injure, or kill sea life long after they are lost and also damage sensitive habitats.*
31. Florida Fish and Wildlife Conservation Commission. 1999-2011. Derelict Trap Retrieval and Debris Removal Program. Available from: http://myfwc.com/RULESANDREGS/SaltwaterTraps_index.htm (Cited 17 Feb 2011). *The FWC has two programs dedicated to removing lost and abandoned traps from state waters. The Spiny Lobster, Stone Crab, and Blue Crab Trap Retrieval Program contracts commercial fishermen to remove fishable traps and the Derelict Trap and Trap Debris Removal Program authorizes volunteer groups to collect derelict traps and trap debris.*
32. Patterson KL, Porter JW, Ritchie KB, Polson SW, Mueller E, Peters EC, Santavy DL, Smith W. 2002. The etiology of white pox, a lethal disease of the Caribbean elkhorn coral, *Acropora palmata*. P Natl Acad Sci. 99:8725-8730. *Description of a lethal coral disease caused by a bacteria.*
33. Buchheim J. 1998. Coral Reef Bleaching. Odyssey Expeditions. Tropical Marine Biology Voyages, Marine Biology Learning Center. Available from: http://marinebiology.org/coralbleaching.htm (Cited 17 Feb 2011). *Description of coral bleaching and causes.*
34. Bruno JF, Peter LE, Harvell CD, Hettinger A. 2003. Nutrient enrichment can increase severity of coral diseases. Ecol Lett. 6:1056-1061. *Corals exposed to high nutrient concentrations bleached and became diseased more readily than controls.*
35. Lirman D, Fong P. 2007. Is proximity to land-based sources of coral stressors an appropriate measure of risk to coral reefs? An example from the Florida Reef Tract. Mar Poll Bull. 54:779-791. *Risk is not always directly related to a water quality gradient.*
36. Kennedy J. Learn About Corals and Coral Reefs. A Round-up of Coral Facts and Information . About.com. Guide. Available from: http://marinelife.about.com/od/habitatprofiles/tp/coralsroundup.htm (Cited 17 Feb 2011). *What are corals, how do they grow, and what are threats?*
37. Ault JS, Smith SG, Bohnsack JA, Luo J, Harper DE, McClellan DB. 2006. Building sustainable fisheries in Florida's coral reef ecosystem: positive signs in the Dry Tortugas. Bull Mar Sci. 78:633-654. *No-take marine reserves in conjunction with traditional fisheries management can help build sustainable fisheries.*
38. Bellwood DR, Hughes TP, Folke C, Nystrom M. 2003. Confronting the coral reef crisis. Nature 429:827-833. *Fisheries management and establishment of marine protected areas are essential to stem worldwide decline of coral reefs.*

Further reading

Aeby GS, Santavy DL. 2006. Factors affecting susceptibility of the coral *Montastraea faveolata* to black-band disease. Mar Ecol Prog Ser. 318:103-110. *Variables, such as potential stressors and disease vectors, could contribute to the patterns of black-band disease observed in the field.*

Ault JS, Bohnsack JA, Smith SG, Jiangang L. 2005. Towards sustainable multispecies fisheries in the Florida, USA, coral reef ecosystem. Bull Mar Sci. 76:595-622. *South Florida coral reefs generated an estimated 71,000 jobs and US $6 billion in economic activity in 2001. These ecosystem goods and services, however, are threatened by increased exploitation and environmental changes from a rapidly growing regional human population.*

Baker DM, MacAvoy SE, Kim K. 2007. Relationship between water quality, δ15N, and aspergillosis of Caribbean sea fan corals. Mar Ecol Prog Ser. 34:123-130. *A positive relationship was detected between prevalence of aspergillosis and long-term total nitrogen concentration. Disease severity was positively related to the ratio between dissolved inorganic nitrogen and total phosphorus over both short and long terms.*

Bryant D, Burke L, McManus J, Spalding M. 1998. Reefs at Risk: A map-based indicator of threats to the World's coral reefs. World Resources Institute, International Center for Living Aquatic Resource Management, World Conservation Monitoring Centre, United Nations Environment Programme, 60 pp. *Maps showing global status of coral reefs.*

Dustan P. 1999. Coral reefs under stress: Sources of mortality in the Florida Keys. Nat Resour Forum 23:147-155. *A description of mortality factors that contribute to the declining health of reefs, including bleaching, sedimentation, algal overgrowth and pollution from point and non-point sources, and the role of humans in the increase of these stresses.*

Furman TB, Heck Jr KL. 2008. Effects of nutrient enrichment and grazers on coral reefs: an experimental assessment. Mar Ecol Prog Ser. 363:89-101. *Nutrient enrichment is an unlikely explanation for the algal overgrowth of coral reefs in the Florida Keys.*

Gardner TA, Cote IM, Gill JA, Grant A, Watkinson AR. 2003. Long-term region-wide declines in Caribbean corals. Science 301:958-960. *Report of massive region-wide decline of corals across the entire Caribbean Basin, with the average hard coral cover on reefs being reduced by 80%, from about 50% to 10% cover, in three decades.*

Ginsburg RN, Shinn EA. 1964. Distribution of the reef-building community in Florida and the Bahamas. Am. Assoc Petr Geol B. 48:527. *Summary of distribution of coral reefs and discussion of reef formation.*

Ginsburg RN, Gischler E, Kiene WE. 2001. Partial mortality of massive reef-building corals: an index of patch reef condition, Florida Reef Tract. Bull Mar Sci. 69:1149-1173. *Patch reefs are by far the most numerous reef type of the Florida Keys Reef Tract. They occur along the inner shelf and they are the nearest reefs to potential anthropogenic impacts from the islands of the Florida Keys by runoff of pollutants, fishing, boating and diving. However, corals do not show clear evidence of direct anthropogenic impacts but do show the negative impacts of storms and of locally unfavorable water quality from the effluent of shallow, lagoonal Florida Bay.*

Glynn PW. 1996. Coral reef bleaching: Facts, hypotheses and implications. Global Change Biol. 2:495-509.

Present evidence indicates that the leading factors responsible for large-scale coral reef bleaching are elevated sea temperatures and high solar irradiance, especially ultraviolet wavelengths, which may frequently act jointly.

Gibson PJ, Boyer JN, Smith NP. 2008. Nutrient mass flux between Florida Bay and the Florida Keys National Marine Sanctuary. Estuar Coasts 31:21-32. *System-wide budgets indicate that the contribution of Florida Bay waters to the inorganic nitrogen pool of the Keys coral reef is small relative to offshore inputs.*

Hallock, P. 2000. Symbiont-bearing foraminifera: harbingers of global change? Micropaleontology 46:95-104. *Foraminifera are susceptible to ongoing anthropogenically produced global changes.*

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno J, Casey KS, Ebert C, Fox HE, Fujita R et al. 2008. A global map of human impact on marine ecosystems. Science 319: 948-952. *Over 40% of the oceans are heavily affected by human activities and few if any areas remain untouched.*

Hughes T, Szmant AM, Steneck R, Carpenter R, Miller S. 1999. Algal blooms on coral reefs: What are the causes? Limnol Oceanogr. 44:1583-1586. *The concept of a definitive nutrient threshold for all coral reefs is not valid. With few exceptions, algal abundance on coral reefs was low until the die-off of the long-spined sea urchin.*

Kim K, Harvell CD. 2004. The rise and fall of a six-year coral-fungal epizootic. Am Nat Suppl. 164:S52-S63. *The study follows the outbreak of aspergillosis of sea fans in the Florida Keys and shows the rapid outbreak and eventual decline of the disease as susceptible individuals are lost.*

Jackson JBC. 1997. Reefs since Columbus. Coral Reefs 16 Suppl: S23-S32. *Caribbean coastal ecosystems were severely degraded long before ecologists began studying them.*

Jones GP, McCormick MI, Srinivasan M, Eagle JV. 2004. Coral decline threatens fish biodiversity in marine reserves. P Natl Acad Sci. 101(21): 8251-8253. *The worldwide decline in coral cover has serious implications for the health of coral reefs. But what is the future of reef fish assemblages? Marine reserves can protect fish from exploitation, but do they protect fish biodiversity in degrading environments? The answer appears to be no.*

LaJeunesse TC. 2002. Diversity and community structure of symbiotic dinoflagellates from Caribbean coral reefs. Mar Biol. 141:387-400. *Twenty-eight genetically distinct zooxanthellae (*Symbiodinium*) types were identified. The reef-wide community distribution of these symbionts is dominated by a few types found in many different host taxa, while numerous rare types appear to have high specificity for a particular host species or genus.*

Lapointe B. 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnol Oceanogr. 42:1119-1131. *Argument for establishment of nutrient thresholds for coral reefs.*

Lang J. 1973. Interspecific aggression by scleractinian corals. 2. Why the race is not only to the swift. Bull Mar Sci. 23:260-279. *Fast-growing corals often employ overtopping competitive strategies and other aggressive behaviors are used by slow-growing species. One type of aggressive behavior involves the use of extruded digestive filaments and sweeper tentacles.*

Lesser MP, Bythell JC, Gates RD, Hohnstone RW, Hoegh-Guldberg O. 2007. Are infectious diseases really killing corals? Alternative interpretations of the experimental and ecological data. J Exper Mar Biol Ecol. 346:36-44. *Coral diseases with rare exception are opportunistic infections secondary to physiological stress that results in reduced host resistance.*

Lidz BH. 2004. Environmental quality and preservation – fragile coral reefs of the Florida Keys: Preserving the largest reef ecosystem in the continental U.S.. U.S.G.S., Open-File Report 97-453, 7 p. *Coral sand percentages mimic loss of reef-building corals. Sands from Miami to Key West contain up to or greater than 30% coral grains. In some areas along the outer margin off the Middle and Lower Keys, where coral mortality is the highest, coral sand grains exceed 60%. These percentages imply that reefs are in peril.*

Lidz BH. 2006. Pleistocene corals of the Florida Keys: Architects of imposing reefs- why? J Coastal Res. 22:750-759. *With time, space, lack of bay waters, and protection from the Gulf of Mexico by an elongated landmass during periods of lower sea level, corals thrived in clear oceanic waters of the Gulf Stream.*

Lidz BH, Hine AC, Shinn EA, Kindinger JL. 1991. Multiple outer-reef tracts along the South Florida bank margin: Outlier reefs, a new windward-margin model. Geology 19:115-118. *Formation and location of four parallel tracks of outlier reefs in the Lower Florida Keys.*

Lipp EK, Futch JC, Griffin DW. 2007. Analysis of multiple enteric viral targets as sewage markers in coral reefs. Mar Pollut Bull. 54:1897-1902. *Of 100 coral and water samples, 40 contained genetic material from one or more human enteric (intestinal) viruses.*

Mayer AG. 1914. The effects of temperature upon tropical marine animals. Pap Tortugas Lab Carnegie Inst. 6:1-14. *Classic study on tolerance of corals to temperature.*

Porter JW. 1987. Species profiles: Life histories and environmental requirements of coastal fishes and invertebrates (south Florida): Reef-building corals. U.S. FWS Biol. Rept. 82(11.73), TR EL-82-4, 31 p. *Summary of growth, depth distribution, effects of hurricanes, predation, disease, and effects of turbidity and sedimentation on four species of reef-building corals.*

Porter JW, Battey JF, Smith GJ. 1982. Perturbation and change in coral reef communities. P Natl. Acad. Sci. 79:1678-1681. *Ninety-six percent of surveyed shallow-water Dry Tortugas reef corals died during the severe winter of 1976-1977. Death occurred during the mid-January intrusion of 14°C water onto the reef.*

Porter JW, Lewis SK, Porter KG. 1999. The effect of multiple stressors on the Florida Keys coral reef ecosystem: A landscape hypothesis and a physiological test. Am Zool. 32:625-640. *Changes in land use and water management in south Florida altered the quality and quantity of water flowing into Florida Bay. By the 1980s, reduced flow and drought resulted in hypersalinity in the bay and possibly affected coral communities in the bay and in the Florida Keys National Marine Sanctuary.*

Porter JW, Meier OW. 1992. Quantification of loss and change in Florida reef coral populations. Am Zool. 32:625-640. *Report of high coral mortality during periods without major hurricanes due to disease and bleaching. Loss at rate observed cannot be sustained.*

Porter JW, Porter KG (eds.). 2002. The Everglades, Florida Bay, and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook. CRC Press, Boca Raton, FL, 1000 p. *Contributed papers focused on the land-sea interface of south Florida, including the Everglades, Florida Bay, Florida Reef Tract, modeling, management, and conservation.*

Richardson LL. 1998. Coral diseases: What is really known? Trends Ecol Evol.13:438-443. *Reports of new and emerging coral diseases have proliferated in recent years. Many of these diseases, however, have been described solely on the basis of field characteristics, and in some instances there is disagreement as to whether an observed coral condition is actually a disease.*

Riegl BM, Dodge RE (eds.). 2008. Coral Reefs of the World. Vol. 1. Coral Reefs of the U.S.A. Dordrecht: Springer-Verlag. 803 p. *Compilation of papers on geology, biology, and management of coral reefs of U.S.A.*

Ritchie KB. 2006. Regulation of microbial populations by coral surface mucus and mucus-associated bacteria.

Mar Ecol Prog Ser. 322:1-14. *Temperature increase may lead to an environmental shift from beneficial bacteria and variability in the protective qualities of coral mucus resulting in an overgrowth of opportunistic microbes.*

Roberts HH, Wilson PA, Lugo-Fernandez A. 1992. Biologic and geologic responses to physical processes: examples from modern reef systems of the Caribbean-Atlantic region. Cont Shelf Res. 12:809-834. *Spur and groove orientations reflect changes in direction of waves as they refract across a reef-dominated shelf.*

Rypien KL. 2008. African dust is an unlikely source of *Aspergillus sydowii*, the causative agent of sea fan disease. Mar Ecol Progr Ser. 367:125-131. *Given the global distribution of* A. sydowii*, an evidence of multiple introductions into marine systems, it is likely that this pathogen has been present in marine systems for a long time, and changes in environmental conditions and host immune status are important in patterns of disease outbreaks.*

Santavy DL, Campbell J, Quarles RL, Patrick JM, Harwell LM, Parsons M, MacLauglin L, Halas J, Mueller E, Peters EC, Hawkridge J. 2006. The Epizootiology of Coral Diseases in South Florida. EPA/600/R-05/146. U.S. EPA, Gulf Ecology Division, Gulf Breeze, FL., 20 p. *Comparison of spatial and temporal distribution of coral species composition and coral disease prevalence among regions, reef types, and between survey periods.*

Schutte VGW, Selig ER, Bruno JF. 2010. Regional spatio-temporal trends in Caribbean coral reef benthic communities. Mar Ecol Prog Ser. 402:115-122. *Analysis of 3777 coral cover surveys and 2247 macroalgal cover studies from the Caribbean indicate that these benthic communities have changed relatively little since the mid-1980s.*

Shinn EA, 1966. Coral growth rate, an environmental indicator. J Paleontol 40:233-240. *Growth rates of transplanted and control corals were measured over a 2-year period. Average growth rate of transplanted corals was less than one-half that of the control group. Seasonal fluctuations were correlated with temperature fluctuations. Growth was greatest at temperatures between 28 and 30°C.*

Shinn EA. 1976. Coral reef recovery in Florida and the Persian Gulf. Environ Geol. 1:241-254. *Although corals are devastated on a grand scale during storms, recovery is rapid. A growth rate of 10 cm per year combined with geometrical progression of branch formation accounts for rapid recovery of* Acropora cervicornis.

Shinn EA. 1988. The geology of the Florida Keys. Oceanus 31:47-53. *An analysis of why corals are found where they are in the Florida Keys and the impacts of sea-level rise.*

Shinn EA, Smith GW, Prospero JM, Betzer P, Hayes ML, Garrison V, Barber RT. 2000. African dust and the demise of Caribbean coral reefs. Geophys Res Lett. 27:3129-3032. *Benchmark events, such as near-synchronous Caribbean-wide mortalities of acroporid corals and the urchin* Diadema *(1983) and coral bleaching beginning in 1987, correlate with years of maximum dust flux into the Caribbean.*

Somerfield PJ, Jaap WC, Clarke KR, Callahan M, Hackett K, Porter J, Lybolt M, Tsokos C, Yanev G. 2008. Changes in coral reef communities among the Florida Keys, 1996-2003. Coral Reefs 27: 951-965. *Summary of monitoring hard and soft coral cover from 37 sites annually from 1996-2003. Large-scale changes coincided with bleaching events in 1997 and 1998 and the passage of Hurricane Georges in 1998.*

Sutherland KB, Ritchie KB. 2004. Chapter 16. White-pox disease of the Caribbean elkhorn coral. In: Rosenberg E, Loya Y (eds.). Coral Health and Disease. Heildeberg: Springer-Verlag. p. 298-300. *Bacterial infection causes lethal disease of elkhorn coral.*

Szmant AM. 2002. Nutrient enrichment on coral reefs: Is it a major cause of coral reef decline? Estuaries 25: 743-766. *Factors other than nutrient enrichment can be significant causes of coral death and affect algal cover, including decreased abundance of grazing fishes, grazing sea urchins, coral diseases, and temperature stress.*

Thompson TG. 1958. Thomas Wayland Vaughan. Nat Acad Sci. Biographical Memoirs 32:399-437. *Biography of Thomas Wayland Vaughan 1870 - 1952.*

Vaughan TW, Wells JW. 1943. Revision of the suborders, families and genera of the *Scleractinia*. Geol Soc Am Special Pap. 44:1-363. *Classic work on systematics of hard corals.*

Veron JEN, Stafford-Smith M. 2000. Corals of the World. Townsville: Sea Challengers, Australian Institute of Marine Science. 3 volumes, 1382 p. *A comprehensive review of coral taxonomy and distribution around the globe.*

Vollmer SV, Palumbi SR. 2007. Restricted gene flow in the Caribbean staghorn coral *Acropora cervicornis*: implications for recovery of endangered reefs. J Hered. 9:40-50. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17158464 (Accessed 17 Feb 2011). *Staghorn corals require local source populations for their recovery and that supports small-scale conservation efforts.*

Wagner D, Mielbrecht E, van Woesik R. 2008. Application of landscape ecology to spatial variance of water-quality parameters along the Florida Keys Reef Tract. Bull Mar Sci. 83:553-569. *It is still not known which stressors primarily drive coral community dynamics along the Florida Keys Reef Tract. Both top down (fishing pressure) and bottom up (elevated nutrients) are influential. These may be over-ridden by global-scale processes.*

Wooldridge SA. 2008. Water quality and coral bleaching thresholds: Formalizing the linkage for the inshore reefs of the Great Barrier Reef, Australia. Mar Pollut Bull. 58:745-751. *Improved coral reef management will increase regional-scale survival prospects of coral reefs to global climate change.*

Wooldridge SA, Done TJ. 2009. Improved water quality can ameliorate effects of climate change on corals. Ecol Appl. 19:1492-1499. *Study found a synergism between heat stress and nutrient flux as a major causative mechanism for coral bleaching. Improved coral reef management will increase the regional-scale survival prospects of coral reefs to global climate change.*

Website references

Buddemeir RW, Kleypas JA, Aronson RB. 2004. Coral Reefs and Global Climate Change: Potential Contributions of Climate Change to Stresses on Coral Reef Ecosystems. Available from: http://www.pewclimate.org/docUploads/Coral_Reefs.pdf (Accessed 18 Feb 2011). *An analysis of the current state of knowledge about the potential effects of climate change on U.S. and global coral reef ecosystems.*

Cesar HJS, Burke L, Pet-Soede L. 2003. The Economics of Worldwide Coral Reef Degradation. Cesar Environmental Economics Consulting, Arnhem, and WWF-Netherlands, Zeist, The Netherlands. Available from: http://assets.panda.org/downloads/cesardegradationreport100203.pdf (Accessed 17 Feb 2011). *Worldwide, coral reefs provide each year nearly $30 billion USD in net benefits in goods and services to world economies, including tourism, fisheries, and coastal protection.*

Conservation International. 2008. Economic Values of Coral Reefs, Mangroves, and Seagrasses: A Global Compilation. Center for Applied Biodiversity Science, Conservation International, Arlington, VA, USA. Available from: http://www.conservation.org/documents/CI_Marine_CI_Economic_Values_Coral_

Reefs_Mangroves_Seagrasses_compilation_2008.pdf (Accessed 17 Feb 2011). *Tropical marine and coral reef ecosystems, including mangroves and seagrasses, are vulnerable environmental resources that provide significant economic goods and services and contribute to the livelihoods, food security and safety of millions of people around the world.*

Coral-Reef-Info.com. 2009-2010. Where are Coral Reefs Located? Your Online Guide to Coral Reefs. Available from: http://www.coral-reef-info.com/where-are-coral-reefs-located.html (Accessed 18 Feb 2011). *Ecological requirements for coral reef growth. Coral reefs are found only in those places in the world's oceans where all of the ecological requirements for hard coral growth are met.*

Donahue S, Acosta A, Akins L, Ault J, Bohnsack J, Boyer J, Callahan M, Causey B, Cox C, Delaney J, Delgado G, Edwards K, Garrett B, Keller B, et al. 2008. The state of coral reef ecosystems of the Florida Keys. In: Waddel JE, Clark AM (eds.) The State of Coral Reef Ecosystems of the United States and Pacific Freely Associated States: 2008. NOAA Technical Memorandum NOS NCCOS 73. NOAA/NCCOS Center for Coastal Monitoring and Assessment's Biogeography Team. Silver Spring, MD. p 161-187. Available from: http://ccma.nos.noaa.gov/ecosystems/coralreef/coral2008/ (Updated 7 July 2008; accessed 17 Feb 2011). *Summary of coral reefs, water quality, fin fish, and conservation and management activities in the Florida Keys National Marine Sanctuary.*

Florida Museum of Natural History. Coral Reefs: Geographical Distribution. Available from: http://www.flmnh.ufl.edu/Fish/southflorida/coral/distribution.html (Accessed 18 Feb 2011). *Map of world distribution of coral reefs.*

Graham NAJ, McClanahan TR, MacNeil MA, Wilson SK, Polunin NVC, Jennings S, Chabanet P, Clark S, Spalding MD, Letourneur Y, et al. 2008. Climate warming, marine protected areas and the ocean-scale integrity of coral reef ecosystems. PLoS ONE 2(8) e3039. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2516599/ (Accessed 17 Feb 2011). *Existing no-take marine protected areas had no positive effect on the ecosystem response to large-scale disturbance. This indicates a need for future conservation and management efforts to identify and protect regional refugia, which should be integrated into existing management frameworks and combined with policies to improve system-wide resilience to climate variation and change.*

Helmle KP, Dodge RE, Swart PK, Gledhill DK, Eakin M. 2011. Growth rates of Florida corals from 1937 to 1996 and their response to climate change. Nature Communications 2, No. 215. Available from: http://www.nature.com/ncomms/journal/v2/n3/full/ncomms1222.html (Accessed 10 Mar 2010). *Growth rate of* Montastraea faveolata *has been tolerant to recent climatic change during the period of record.*

Hemond EM, Vollmer SV. 2010. Genetic diversity and connectivity in the threatened staghorn coral (*Acropora cervicornis*) in Florida. PLoS ONE 5(1) e8652. Available from: http://www.ncbi.nlm.nih.gov/pubmed/20111583 (Accessed 17 Feb 2011). *The relative high genetic diversity and connectivity within Florida implies that staghorn coral may have sufficient genetic variation to be viable and resilient to environmental perturbation and disease.*

Kennedy J. 2011. Coral Reefs. About.com Guide. Available from: http://marinelife.about.com/od/habitatprofiles/p/reefs.htm (Accessed 18 Feb 2011). *Summary of threats to coral reefs.*

Mao-Jones J, Ritchie KB, Jones LE, Ellner SP. 2010. How microbial community composition regulates coral disease development. PLoS Biol. 8(3):e1000345. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2846858/ (Accessed 17 Feb 2011). *Stressful conditions, such as a brief warming spell, may cause a shift in resident microbial community in the mucus layer surrounding the coral, resulting in loss of antibiotic activity and growth of pathogenic microbes.*

Mora C. 2007. A clear human footprint in the coral reefs of the Caribbean. P Roy Soc B. 275(1636):767-773. Available from: http://rspb.royalsocietypublishing.org/content/275/1636/767.abstract (Accessed 17 Feb 2011). *Long-term stability of coral reefs requires a holistic and regional approach to the control of human-related stressors in addition to the improvement and establishment of new marine protected areas.*

National Oceanic and Atmospheric Administration, Coral Reef Information System. Glossary. Available from: http://coris.noaa.gov/glossary/ (Updated 2 Dec 2010; accessed 18 Feb 2011). *A glossary of over 6,000 technical terms, with their definitions, explanations, and illustrative materials to help the student or layperson, as well as the professional scientist and manager, understand the complex language and terminology of coral reef ecosystem science.*

National Oceanic and Atmospheric Administration, Coral Reef Information System. Available from: http://coris.noaa.gov/about/diseases/ (Updated 2 Dec 2010; accessed 18 Feb 2011). *Summary of diseases of reef-building corals.*

Oak Ridge National Laboratory. A quick background to the last ice age. Biological and Environmental Sciences. Available from: http://www.esd.ornl.gov/projects/qen/nerc130k.html (Updated 2 Dec 1997; accessed 27 Jul 2011). *A summary of events during the last 130,000 years of glacial and interglacial periods.*

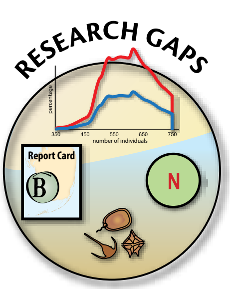
Vollmer SV, Palumbi SR. 2007. Restricted gene flow in the Caribbean staghorn coral *Acropora cervicornis*: implications for recovery of endangered reefs. J Hered. 9:40-50. Abstract available from PubMed: http://www.ncbi.nlm.nih.gov/pubmed/17158464 (Accessed 17 Feb 2011). *Staghorn corals require local source populations for their recovery that supports small-scale conservation efforts.*

Vollmer SV, Kline DI. 2008. Natural disease resistance in threatened staghorn corals. PLoS ONE 3(11) e3718. Available from: http://www.ncbi.nlm.nih.gov/pmc/articles/PMC2579483/ (Accessed 17 Feb 2011). *Resistant corals may explain why pockets of staghorn corals have been able to survive the white-band disease epidemic. Understanding disease resistance may be a critical link in restoring populations.*

5. SEAGRASS HABITATS

Seagrass Habitats
Chapter Recommendations

- Develop a **comprehensive conservation plan** for south Florida seagrasses.
- Recognize the importance of healthy seagrass communities to the ecology, economy, and quality of life in south Florida and educate the public on measures that can be taken to **conserve seagrass resources**.
- Develop **education and outreach programs** to garner community stewardship and individual responsibility for seagrass conservation.
- Promote a **dialogue between researchers and environmental managers** to assure that research is relevant to management needs and managers understand the implications of research results.
- Protect seagrasses from **dredge and fill activitie**s through strong regulatory programs and adequate enforcement, and quantitatively assess success and failure of seagrass mitigation efforts.
- Support **restoration of seagrasses** which have suffered long-term loss in order to bolster areal extent and facilitate ecosystem recovery.
- Reduce sources of pollution to seagrass beds from **land-based point and nonpoint sources** through watershed planning.
- Decrease **nutrient inputs** to coastal waters that negatively impact seagrass health and growth by supporting and implementing improved wastewater and stormwater collection and treatment systems.
- Support data collection required to develop **numeric nutrient criteria** for marine and coastal waters.



- Develop quantitative functional assessment tools to evaluate seagrass ecosystem integrity as **early warning signals** of ecosystem decline. Identify metrics to assess seagrass "health."
- Determine **causes of changes** in seagrass species composition and coverage.
- Further **develop models to predict changes** to benthic habitats with changes in water quality and delivery patterns to coastal areas.
- Conduct field and laboratory exposure experiments on the effects of **multiple stressors** to seagrass survival, species composition, and community structure.
- **Identify and quantify linkages** between seagrass meadows and other marine habitats.
- Develop dependable and cost-effective **seagrass restoration techniques**.

Chapter title page: Widgeon grass bed with flowers. T. Carruthers, IAN Image Library.

- Continue long-term quantitative monitoring of seagrasses throughout south Florida to **regularly assess status and trends** and evaluate management actions.
- **Develop methods to map seagrasses** using new technologies and sensing platforms.
- Monitor indicators of **seagrass health** to detect stress so the source of stress can be quickly identified and removed.
- Regularly assess **impacts of turbidity** from large ships and other sources.

C. Avila - Miami-Dade County DERM

Researchers collect data on the health, abundance, and diversity of seagrass species in south Florida.

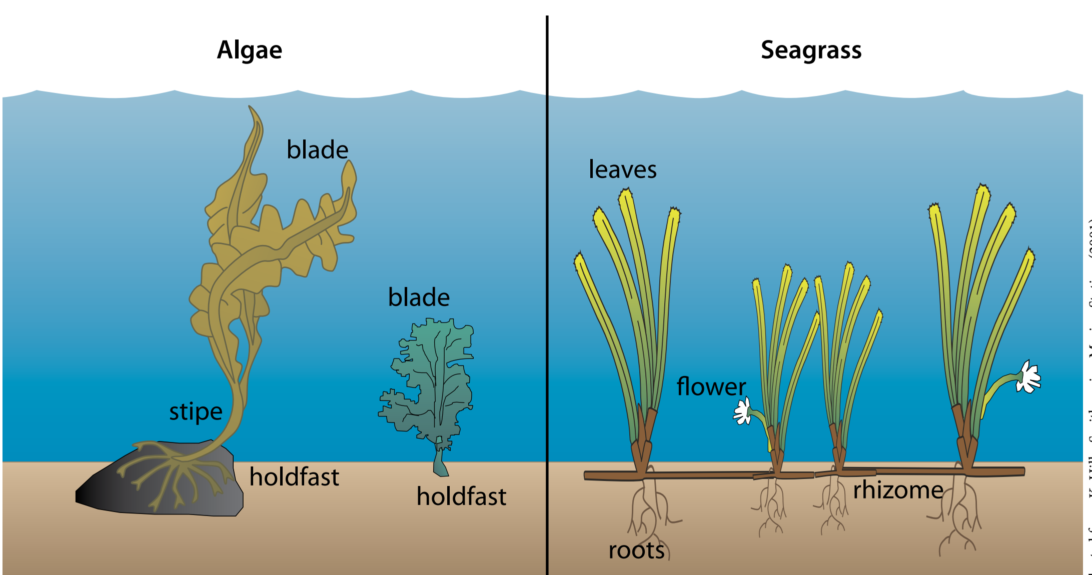
Introduction

What are seagrasses?

Seagrasses are submerged plants that grow on the seafloor in bays, lagoons, and shallow coastal waters where there are soft sediments for anchoring their roots and adequate light penetration through the water column for photosynthesis. They evolved from land plants during the Cretaceous Period, a time when dinosaurs roamed the Earth. They reproduce underwater by producing flowers, fruits, and seeds. Pollen and seeds are transported by water currents.[1] Seagrasses are easily distinguished from seaweeds (i.e., algae) in that seagrasses have a vascular system to transport nutrients from roots to leaves and true roots that penetrate the sediment. Seaweeds lack roots but may have a holdfast that attaches to surfaces and they rely on diffusion for intercellular transport.[2]

South Florida has seven species of seagrasses

There are about 60 species of seagrasses worldwide, and seven occur in south Florida: turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), shoal grass (*Halodule wrightii*), widgeon grass (*Ruppia maritima*), paddle grass (*Halophila decipiens*), star grass (*Halophila engelmannii*), and Johnson's seagrass (*Halophila johnsonii*).[3] Turtle grass is the most common seagrass in south Florida and is found in areas with stable salinities, stable sediments, and high light penetration. Manatee grass is common in mixed seagrass beds or in dense monospecific stands, often in slightly deeper water than turtle grass. Shoal grass is found in mixed beds and in disturbed areas. It is a fast-growing, "pioneer" species that is the first to colonize barren or disturbed sediments. It tolerates exposure to air and fluctuating salinities and can be found in shallower water than turtle and manatee grass, but also has a deeper maximum depth than turtle grass or manatee grass. Widgeon grass is sometimes not considered a true "sea" grass because its distribution is restricted to areas near freshwater sources. It is a shallow water species, most common in bays and creeks with brackish salinities.



Benthic algae have a holdfast and transport nutrients by diffusion. True seagrasses are flowering vascular plants with an internal transport system to transport nutrients and roots that penetrate the sediment.

The seagrass meadow in south Florida is the largest documented, semicontinuous seagrass meadow on earth, covering approximately 15,200 km^2 (5900 mi^2). This view of a portion of the seagrass meadow contains mixed seagrass species, turtle grass (wide blades) and manatee grass (narrow blades).

Star grass and paddle grass are generally restricted to low light environments and are found in deeper or turbid waters. Star grass is uncommon, but paddle grass forms extensive offshore meadows on the Southwest Florida Shelf. Johnson's seagrass is a federally threatened species and is most common in the Indian River Lagoon and northern Biscayne Bay.[4] Male flowers of Johnson's seagrass have never been observed; thus, populations are most probably maintained exclusively by vegetative growth and reproduction.[5]

South Florida has extensive seagrass meadows

Seagrasses are an important component of coastal marine environments, but there are few places in the world where seagrasses are as dominant as they are in south Florida. Here they are found growing in the shadows of skyscrapers in Biscayne Bay to the pristine clear waters of the Dry Tortugas. In total, there are approximately 15,200 km^2 (5900 mi^2) of seagrasses in south Florida, making it the largest documented semicontinuous seagrass meadow on the planet.[6] Because of the importance of seagrasses to the coastal economy of south Florida, the resource has been well studied compared to other regions of the world. It is probable that there are other large seagrass ecosystems in regions without the economic incentive or scientific infrastructure necessary to document their spatial extent, such as some islands in the Indo-Pacific and offshore banks in the Caribbean.

Seagrasses perform important ecosystem functions

Like terrestrial grasslands, seagrasses provide food and a complex, three-dimensional habitat for a diverse assemblage of invertebrates and vertebrates. Infaunal organisms (e.g., crabs, shrimp, worms) live within sediments stabilized by seagrass roots and rhizomes. Epibenthic organisms (e.g., snails, starfish, urchins) live on the sediments. Grazers and predators move throughout the community harvesting their prey.

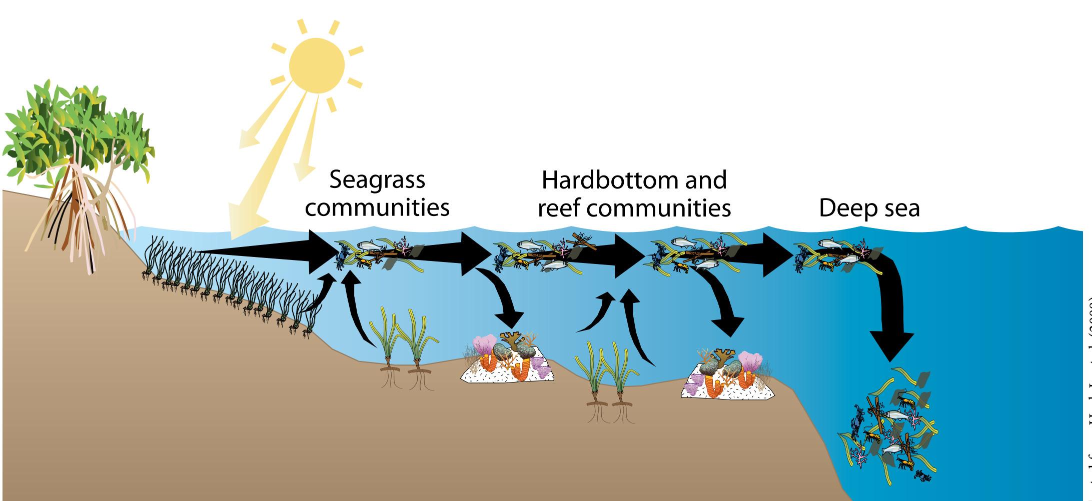
Primary productivity

Seagrasses have high levels of primary production due to their efficient uptake and utilization of nutrients and the high turnover rate of leaves. These characteristics are a major factor in their ability to maintain high rates of productivity in relatively low nutrient environments.[7] Productivity varies largely because of the range of environments where seagrasses are found in the region. Productivity also varies with season; highest production rates occur in summer months at about double the annual average rate. Seagrass leaves are colonized by epiphytes which contribute to overall seagrass primary production. The total productivity of a seagrass bed in south Florida, including the productivity of benthic algae within the bed, can be as high as 9.4 grams per square meter per day (g/m^2/d), which is about five times the average productivity of cultivated cropland (1.8 g/m^2/d).[6]

Seagrass leaves are an important source of energy to many organisms within the meadows and adjacent communities. Primary consumers of seagrasses and their epiphytes include green sea turtles, manatees, snails, sea urchins, and some fish and waterfowl. Sea urchins can become locally abundant on occasion, and can consume a large amount of seagrasses locally.[8] The reasons for periodic population explosions of sea urchins in seagrass beds are not known.

Nutrient cycling

Seagrasses release dissolved organic carbon into the water column. This is an important food source for microorganisms at the base of the marine food web. Seagrass leaves and associated microflora that are not eaten directly may be exported to other components of the marine ecosystem, or be broken down into detritus (i.e., dead plant material) by microbes within the seagrass bed. It is estimated that more than 75% of manatee grass leaves that are shed are exported offshore.[9] Seagrass detritus is an important food source for many organisms in the marine ecosystem. It is possible that seagrass beds export more energy in the form of detritus than they did in the past because of the loss of populations of large herbivores.[9] Seagrass, epiphytes, and benthic algal detritus provide a carbon source for a diverse variety of small, seagrass-associated organisms, including protozoans, nematodes, and marine worms. Those animals then become available as food for intermediate trophic levels, including microcrustacea (e.g., amphipods,



Seagrasses fix carbon from seawater using light energy from the sun and produce carbon sources that fuel the seagrass food web. Leaves, detritus, and animals that are exported from seagrass beds are a "conveyor belt" of energy to hardbottom, coral reef, and deep sea communities.

isopods), decapods (e.g., shrimp, crabs), gastropods, and small fishes. They are in turn consumed by larger finfish that live in the seagrasses (e.g., speckled trout) or visit the seagrass meadows to forage (e.g., gray snapper).[9,10] Although not widely recognized, large amounts of seagrass leaves and detritus are exported beyond the continental shelf and are available as energy sources for offshore, deep sea communities. Photographs of the deep seafloor confirm that an abundance of seagrass leaves collect on the ocean bottom and fuel offshore food webs.[9]

Energy cycling

Coral reef communities are enhanced when they occur adjacent to seagrass meadows. Some predators that live on reefs forage in seagrass meadows, including grunts, parrotfish, squirrelfish, moray eels, and others. Diurnal migrations of foraging reef fish contribute an important nutrient subsidy to coral reefs by depositing feces, thus constituting a major energy linkage between corals and seagrass meadows.[9] A similar energy connection has been reported between seagrasses and mangroves.[9,11]

Seagrasses also export energy in the form of animals that travel between grass beds and adjacent marine communities. A prime example is the mass exodus of pink shrimp from seagrass nursery beds in Florida Bay to the offshore spawning grounds in the Dry Tortugas.[9] Shrimp are a main component of the seagrass detrital food chain and become a food source for higher trophic levels not only within the grass bed, but in adjacent marine waters as they make their spawning migrations. Pinfish (*Lagodon rhomboides*) are also a component of the "conveyor belt" of nutrients from seagrasses, where they grow, to offshore, where they mature and spawn.[9,12] Many predators within the marine ecosystem feed on shrimp and pinfish, and seagrasses are the base energy source for those food chains.

Seagrass distribution is controlled by different factors

Seagrasses inhabit a physically challenging environment. There are five main environmental factors that control the distribution of seagrasses in south Florida: sediment, salinity, temperature, the amount of available nutrients, and light.[13] In general, these requirements vary for different seagrass species.

Sediment type

All seagrasses require soft sediments, muds and sands, that can be penetrated by their roots and rhizomes (underground horizontal stems). Seagrass leaves emerge from their underground vertical stems called "short shoots." Sediments in south Florida estuaries and nearshore marine environments consist predominantly of calcium carbonate muds and sands. The roots and rhizomes anchor the plant and form a firm mat over the sea bottom. Thus, they are able to withstand moderate wave energy and storm surges. The presence of seagrasses moderates wave energy due to friction over the surface of the bed. Once seagrasses are established in an area, they trap fine inorganic and organic particles because of the baffling effect of the seagrass leaves.[7] Sediment requirements vary with seagrass species. For example, turtle grass rhizomes may penetrate as deep as 25 cm (10 in), whereas roots of *Halophila* species barely grow below the substrate surface.

Salinity

Widgeon grass can live in a wide range of salinities, from freshwater to full seawater strength. It has been reported to survive a wide range of salinities, if the change in salinity is gradual.[14] This seagrass normally lives in freshwater or in areas with reduced salinities (estuarine conditions) and high nutrient supply, such as in bays and creeks entering the north portion of Florida Bay. Manipulation of water delivery to the transition zone due to historical drainage projects in the

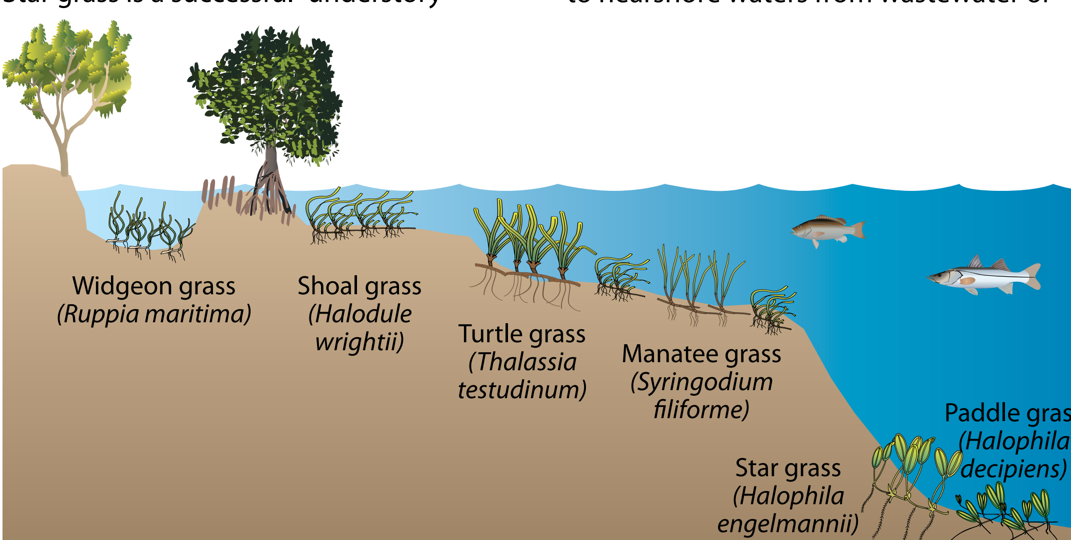
Everglades has resulted in rapid salinity changes from freshwater during rain events to high salinities during dry, hot periods. These rapidly changing extremes in salinity have resulted in widespread loss of widgeon grass.[15]

Depth

Shoal grass can occur in a wide range of depths, and is particularly common in shallow water. It can also tolerate a wide range of salinities and is common in disturbed sediments. Those broad tolerances make it an ideal "pioneer" species. Turtle grass can live at depths nearly as shallow as shoal grass but does best in full strength seawater salinity. Manatee grass also requires stable salinities and is generally found deeper than turtle grass. However, it is not uncommon to have all three of the common seagrasses growing in the same grass bed. Star grass and paddle grass occur in full seawater salinity in areas as deep as 40 meters (130 feet), where there is adequate light to support photosynthesis. In general, shoal grass and turtle grass require about 10% – 20% of surface light reaching the bottom. Star grass is a successful "understory" species that can grow in the shade of other seagrasses. It has also has been found growing as deep as 90 m (295 ft) off Cuba.[16] Paddle grass is also a shade tolerant species and can form meadows in areas where as little as 5% of surface light reaches the bottom.[13,17]

Nutrients

Seagrasses are adapted to growing in the clear, nutrient-poor marine waters of south Florida. Unlike land plants, they absorb nutrients through all parts of the plant, not just the roots, and are very efficient in taking up nutrients from water and sediments. Because they take up nutrients quickly, they are good "sentinels" of water quality conditions, including enrichment or shortage of nutrients (e.g., nitrogen, phosphorus). The ratio of nitrogen to phosphorus found in seagrass leaves of turtle grass shows that, on average, phosphorus is in short supply in waters in eastern Florida Bay and close to shore in the Florida Keys. At the western boundary of Florida Bay and near the Atlantic bank reef tract, there is ample phosphorus but a shortage of nitrogen.[18,19] Thus, adding phosphorus to nearshore waters from wastewater or



Generalized distribution of seagrass species with depth. Widgeon grass grows in freshwater areas or areas with reduced salinities, such as in tidal creeks, ponds, and embayments. Shoal grass tolerates shallow water and disturbed conditions. Turtle grass grows somewhat shallower than manatee grass. Shoal grass, turtle grass, and manatee grass can commonly be found at the same depth. Paddle grass and star grass are found in areas with reduced light penetration due to shading, depth, or turbidity.

stormwater may stimulate the growth of seagrasses. Indeed, that has been seen in an investigation of historical aerial photographs that compare the shoreline of the Keys in the 1950s and 1990s. Prior to intense land development, turtle grass coverage near the islands was sparse; coverage increased substantially as the shoreline was developed.[20] But, as the nutrient supply continues to increase, it results in a change in species composition as slower growing species (e.g., turtle grass) are replaced by faster growing ones (e.g., shoal grass). At high nutrient levels, all seagrass species are replaced by macroalgae and microalgae.[21] That trend of increased macroalgae within seagrass beds has begun to appear in south Florida.[22] If continued, it could result in the loss of the seagrass component of the benthic community and dramatic changes in community structure and function. Animal species dependent upon seagrasses for food and shelter may be replaced by less desirable species that thrive in phytoplankton-dominated systems, such as jellyfish. As nutrients increase, the growth of phytoplankton results in shading that further stresses seagrasses due to light limitation. As seagrasses die, sediments can become easily disturbed and further exacerbate light penetration and release more nutrients to the water column to further fuel phytoplankton blooms.

Periodic seagrass die-offs occur in Florida Bay

Historically, Florida Bay was an estuary and had a diverse seagrass community. It received freshwater runoff from the Everglades through tidal creeks along its north shore and from Shark River to the west. However, beginning in the 1950s, drainage projects redirected much of the freshwater away from the Everglades and salinities in the Bay increased. The seagrass community became dominated by a thriving monoculture of turtle grass.[23] A period of hot, dry conditions in the mid 1980s resulted in very high salinities and warm temperatures. Turtle grass production was high, but nighttime respiration was so high that it stripped all of the oxygen from the water. Warm water does not hold as much oxygen as cooler water. The resulting anoxic conditions severely stressed the seagrasses and resulted in the formation of toxic sulfides in the sediments. Lack of oxygen and the presence of toxic sulfides killed the stressed plants and resulted in a seagrass die-off in large areas of western and central Florida Bay beginning in 1987.[24] Stressed seagrasses were also attacked by a parasitic slime mold (*Labyrinthula* sp.) that also killed weakened plants at several locations in the Bay. Salinity plays an important role in controlling infection of turtle grass by *Labyrinthula*. Both laboratory and field data show that the slime mold prefers higher salinities and is not infectious to seagrasses at salinities below 15 parts per thousand (ppt).[25,26]

By 1990, the rate of die-off slowed and shoal grass began recolonizing areas left bare from turtle grass death. But in 1991, nutrients from dead seagrasses and sediments no longer bound by seagrass root mats resulted in widespread phytoplankton blooms in the Bay. The green, turbid water further stressed the remaining seagrasses, including the pioneer shoal grass growths, by decreasing the light penetration below that required for seagrass growth.

Seagrass die-off continues in several parts of the Bay, but most of the areas of original die-off are recovering to the point where turtle grass is currently replacing the pioneer shoal grass. Hopefully, Everglades restoration activities will result in increased freshwater flows that will allow seagrasses to once again thrive in Florida Bay. If done correctly, salinities in the Bay will be returned to more estuarine conditions than were present in 1987, and that should result in a more diverse and stable seagrass community than a pure turtle grass monoculture.

Humans cause damage to seagrasses

Seagrass habitats support important commercial and recreational fisheries.

Fishing for species that depend on healthy seagrass habitats for food and habitat, such as speckled trout, redfish, bonefish, and tarpon, contributes many millions of dollars per year to the south Florida economy. Healthy seagrass habitats affect adjacent habitats, such as coral reefs, and contribute to the south Florida economy by attracting tourists that support charter boats, marinas, hotels, restaurants, tackle shops, dive shops, and many other

A.V. Uhrin - NOAA

Lobster traps have a heavy concrete base. When left in place for 6 weeks or longer, they cause long-term damage to seagrasses. Of the 495,000 traps currently permitted in this fishery, tens of thousands are lost annually through routine fishing practices and remain in place. Trap losses are amplified during storms and hurricanes. Derelict lobster traps are problematic because they continue to trap, injure, or kill sea life long after they are lost. Also, they can be moved by waves and currents and cause widespread destruction of benthic communities.

businesses. The Florida Department of Environmental Protection has estimated that each acre of seagrass has an economic value of approximately $20,500 per year (2001 dollars).[27]

It has been estimated that approximately 20% – 100% of seagrasses have been lost in estuaries in the Gulf of Mexico.[28] There are many causes of the losses and they vary by location. They include storm events, water drainage manipulations, physical removal from dredging and filling activities, smothering with sediments, light extinction from turbidity, docks and anchored structures, and phytoplankton blooms, inputs of excess nutrients, trampling, fishing gear (e.g., lobster traps), boat groundings, and propeller scarring.[29,30,31] Human-induced impacts are chronic, insidious, often synergistic, and can have long-lasting effects. Seagrasses are found at the downstream position in watersheds and are susceptible to perturbations from many upstream sources. Stresses can eliminate seagrasses completely or produce patchy, discontinuous beds. Fragmented beds do not provide the same ecological values as continuous meadows.[32]

Seagrasses require consistent management throughout south Florida

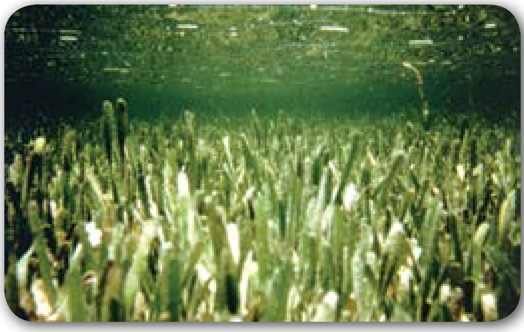
Much of the focus of seagrass management has been on restoration of areal coverage of damaged or destroyed areas. Progress has been made in seagrass restoration activities in recent years, but full and complete restoration is still largely a "hit or miss" activity and it is expensive.[32] More focus should be given to prevention of seagrass losses through proactive conservation and management of existing resources. Channel marking, no-motor and idle-speed only zones, increased enforcement, and education of the public and boaters on the importance of seagrass conservation are active alternatives to "crisis management", including restoration attempts.[33] Protection and regulatory mechanisms must be put in place and enforced to protect the seagrass meadows.

There is ample evidence from several lines of scientific inquiry to document early warnings of changes in seagrass meadows due to nutrient additions to the waters of south Florida.[22] Managers must give priority to the elimination of upstream activities that can potentially harm seagrass meadows. Protective management of seagrasses is required to conserve this precious resource so that future generations may fully enjoy the benefits that they provide to the ecology, economics, and quality of life in south Florida.

Seagrasses are unique flowering plants

Michael J. Durako

Seagrasses are found worldwide in tropical to temperate waters and are frequently the dominant biological community in shallow coastal waters. Seagrasses are the only flowering vascular plants that live in the sea. Seagrasses differ from seaweeds in that they have roots, stems, leaves and flowers. They are also not true grasses, but are more closely related to lilies. The name "seagrass" comes from the fact that they form meadows or beds that look much like terrestrial grasslands. The growth forms of seagrasses are the result of reduction and loss of structures not necessary for survival in a liquid medium.



M.J. Durako - UNCW

South Florida turtle grass bed.

Seagrasses are an ancient plant group thought to have colonized the sea during the age of the dinosaurs, about 100 million years ago. To survive in the marine environment, seagrasses had to acquire the ability to tolerate saltwater, to grow submerged, to withstand waves and currents, and to complete their life cycles while submerged. This last characteristic involves submarine pollination and specialized methods for seed dispersal and establishment. For example, in turtle grass, the fruits are buoyant and may float on the surface of the water before they open to release ballasted seedlings that sink to the bottom and produce sticky root hairs to help anchor them to the sediments.

M.J. Durako - UNCW

Male flowers of turtle grass.

M.J. Durako - UNCW

Turtle grass seedling germinating from seed.

Some interesting seagrass facts

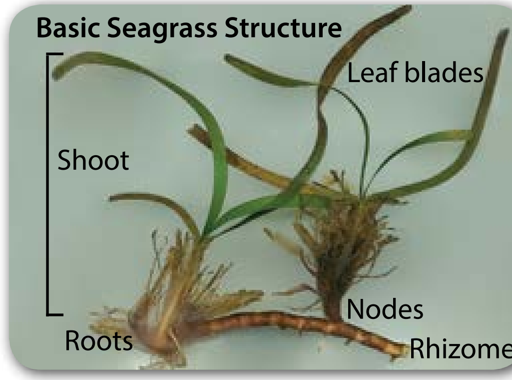
- Some seagrass beds, such as the seagrass beds in Florida Bay, are so large they are visible from space.
- There is a seagrass bed in the Mediterranean Sea that is known to be over 6000 years old.
- Five of the 12 genera of seagrasses found worldwide occur in Florida.
- Seagrass productivity rivals that of agricultural crops, such as rice paddies and corn fields.
- Johnson's seagrass (*Halophila johnsonii*) was the first federally listed threatened marine plant species.
- While most Florida seagrasses live in shallow waters (generally less than 9.1 meters (30 feet)) deep, they may grow in waters as deep as 30.5 m (100 ft).

Seagrass Habitats

There are seven different seagrasses in south Florida

Margaret O. Hall

- Seagrasses are a functional group of submerged, flowering marine plants.
- Seagrasses are relatives of the lily family, but are called seagrasses because they physically resemble terrestrial grasses and form large underwater meadows.
- Approximately 60 seagrass species occur worldwide; 7 seagrass species belonging to 5 genera occur in south Florida coastal waters.



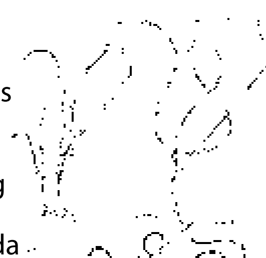
KEY TO THE SPECIES

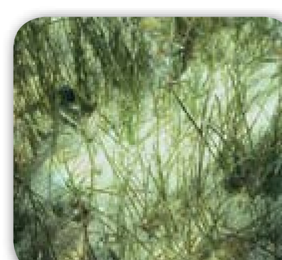
1a. Blades flat in cross-section.......................................2
1b. Blades cylindrical in cross-section..........................*Syringodium filiforme* (Manatee grass)
2a. Blades paddle-shaped or elliptical.......................................3
2b. Blades in pseudo-whorl with clusters of 4-8 leaves...*Halophila engelmannii* (Star grass)
2c. Blades strap-shaped or ribbon-like.......................................4
3a. Blades oval; leaf margins with minute serrations........*Halophila decipiens* (Paddle grass)
3b. Blades linear-elliptical; leaf margins smooth....*Halophila johnsonii* (Johnson's seagrass)
4a. Blades >3 mm wide, usually about 1 cm wide; blade tip rounded.......................................*Thalassia testudinum* (Turtle grass)
4b. Blades<3 mm wide.......................................5
5a. Blades 1-3 mm wide; blade tip notched or dentate..........*Halodule wrightii* (Shoal grass)
5b. Blades up to 1 mm wide, tapering; blade tip pointed ....*Ruppia maritima* (Widgeon grass)

D.S. Littler and M.M. Littler

Shoal grass *(Halodule wrightii)*

- Narrow, flat blades (< 3 millimeters (0.12 inches) wide, 5 – 25 centimeters [2 – 10 in] long) with notched tips
- Fast-growing, pioneer species
- Tolerates desiccation and fluctuating salinities
- Very common species in south Florida

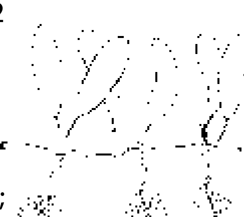




D.W. Crewz - FWRI
R.C. Phillips

Paddle grass *(Halophila decipiens)*

- Paddle-shaped blades (3 – 6 mm [0.12 – 0.24 in] wide, 1 – 2.5 cm [0.4 – 1 in] long) with rounded tips; blades occur in pairs at each node
- Blade margins with minute serrations
- Seeds prolifically
- Locally abundant in estuarine regions; forms extensive offshore meadows in Gulf of Mexico



D.W. Crewz - FWRI
D.S. Littler and M.M. Littler

Star grass *(Halophila engelmannii)*

- Paddle-shaped blades (3 – 6 mm [0.12 – 0.24 in] wide, 1 – 3 cm [0.4 – 1.2 in] long) with pointed tips; Blades occur in whorls at the top of 2 – 4 cm long stalks
- Generally uncommon, but widely distributed in South Florida

D.W. Crewz - FWRI
M.O. Hall - FWRI

Johnson's seagrass *(Halophila johnsonii)*

- Linear-elliptical blades (2 – 4 mm [0.08 – 0.16 in] wide, 0.5 – 2.5 cm [0.2 – 1 in] long); blades occur in pairs at each node
- Blade margins smooth
- Uncommon; endemic to the southeast coast of Florida (Sebastian Inlet to Virginia Key)
- Listed as a threatened species by the National Marine Fisheries Service in 1998

D.W. Crewz - FWRI
L. Morris - SJRWMD

Widgeon grass *(Ruppia maritima)*

- Narrow, flat blades (≤ 1 mm [0.04 in] wide, about 10 – 20 cm [4 – 8 in] long) with sharply pointed tips
- Flowering shoots float prominently on water surface
- Can grow in both fresh and saltwater
- Occurs in both temperate and tropical regions
- Common species in south Florida bays and creeks with brackish salinities

D.W. Crewz - FWRI
T. Carruthers - IAN Image Library

Manatee grass *(Syringodium filiforme)*

- Cylindrical blades (1 – 2 mm [0.04 – 0.08 in] diameter, 10 – 35 cm [4 – 14 in] long)
- Very common species in south Florida
- Often found in mixed beds with turtle grass

D.W. Crewz - FWRI
R. C. Phillips

Turtle grass (*Thalassia testudinum)*

- Broad, flat blades (0.5 – 2 cm [0.2 – 0.8 in] wide, up to 35 cm [14 in] long) with rounded tips
- Slow-growing, climax species
- Most abundant seagrass species in south Florida, Caribbean, and Gulf of Mexico

D.W. Crewz - FWRI
A.V. Uhrin - NOAA

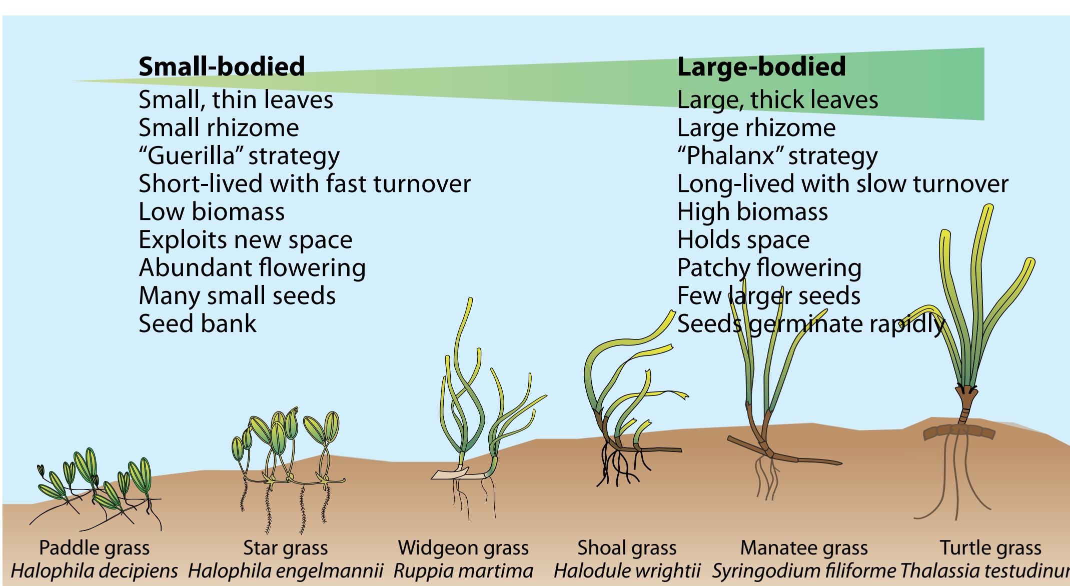
Descriptions and key modified from Eiseman and McMillan (1980); Phillips and Meñez (1998); Dawes, Phillips and Morrison (2004); and Littler, Littler, and Hanisak (2008).

Seagrasses have different life history strategies

Michael J. Durako

All seagrasses are clonal plants. This means that the individual shoots are connected by an underground stem called a rhizome and that they act together as a single physiologically-integrated organism. In clonal plants, individual shoots are called "ramets," and the entire plant is known as the "genet." A major benefit of clonality is the ability to exploit resources and support shoots in different environments. Clonal plants also benefit from indeterminate growth, where each new ramet may produce another. This results in efficient acquisition of space and is one reason that seagrasses may dominate coastal underwater seascapes.

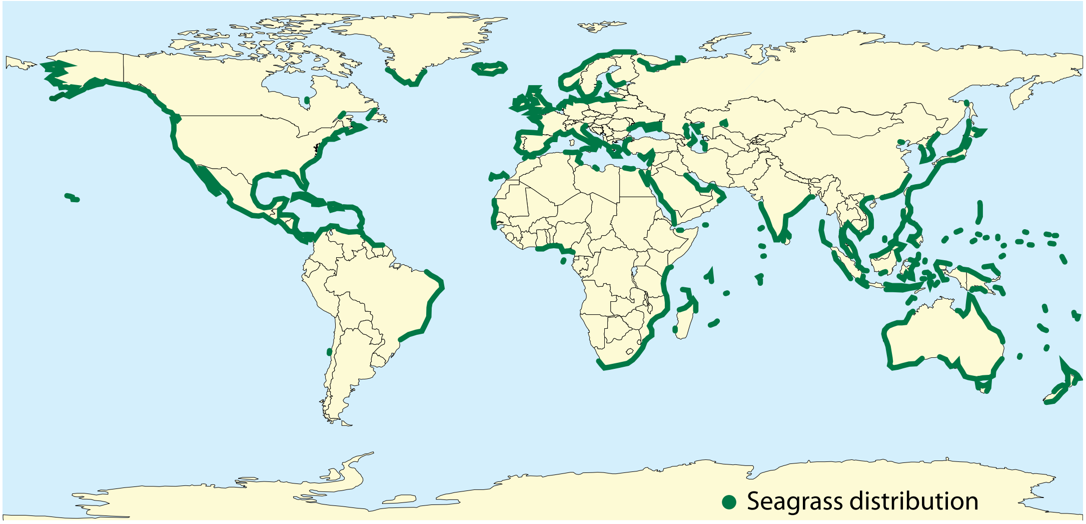
Seagrasses compete for space, and their strategies for competition reflect their growth forms and life history characteristics. In south Florida, seagrasses range from small-bodied plants with thin leaves and small rhizomes (e.g., *Halophila*, *Halodule*, *Ruppia*) to large-bodied plants with thicker leaves and larger rhizomes (e.g., *Syringodium*, *Thalassia*). Small-bodied seagrasses generally exhibit shorter shoot life spans, rapid leaf and rhizome turnover, and produce many small seeds. Large-bodied seagrasses are longer lived with slower turnover rates and they produce larger seeds that germinate in the season they are produced. Small-bodied seagrasses usually exhibit what is known as a "guerilla" competition strategy which includes fast growth in an attempt to find resources quickly. In this strategy, resources are directed to the points of new growth, with little support for "holding" previously acquired areas. In contrast, slow growth, and a reliance on new shoots to support older shoots in an attempt to increase shoot density and slowly conquer and hold space, distinguishes the "phalanx" strategy employed by the large-bodied seagrasses. Guerilla plants tend to be opportunistic, more responsive to changes in environmental conditions and recover rapidly from disturbances. Phalanx species tend to dominate more stable environments and are more resistant to short-term stresses.



The south Florida marine ecosystem contains the largest documented seagrass bed on Earth

James W. Fourqurean

Seagrasses occur around the globe where sands and muds cover the bottom and where sufficient sunlight can penetrate to the bottom. Such areas are found from polar regions to the tropics, and on all continents except for Antarctica. The global nature of seagrass distribution is different than the other conspicuous coastal ecosystems: salt marshes and kelp forests are restricted to temperate climes, and mangrove forests and coral reefs are only found in tropical and subtropical regions.

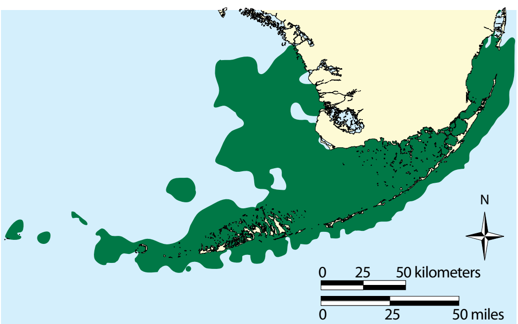


The global distribution of seagrasses. Seagrasses are found from polar regions to the tropics and on all continents except Antarctica.

The best estimate of global total area covered by seagrass meadows is 177,000 km^2 (68,350 mi^2). This estimate is based on seagrass beds that have been mapped using modern methods and is known to be an underestimate because of the lack of data from many tropical areas where mapping the extent of seagrasses has been hampered by lack of scientific capacity and funding. An upper estimate of the area of the globe that supports seagrasses, based on maps of water clarity and bottom type, is about 600,000 km^2 (232,000 mi^2), but even this is likely an underestimate given the large areas of the globe still to be surveyed.

Sunlight can penetrate to the bottom in the clear waters along the coast of southern Florida and the Florida Keys and allows seagrasses to grow as deep as 30.5 meters (100 feet). However, across much of the area, the soft sands and muds required for seagrasses to grow are restricted to shallower depths inshore of the barrier reef. An exception to this condition occurs on the broad and slowly sloping waters of the Southwest Florida Shelf north of the Florida Keys. The waters of the Gulf of Mexico also are generally more turbid than those of the reef tract, so light becomes limiting in areas where there is still sand and mud on the bottom.

In south Florida, seagrasses can be found growing in the shadows of skyscrapers in highly urbanized Biscayne Bay to the pristine clear waters of the Dry Tortugas. In total, there are about 15,200 km^2 (5900 mi^2) of seagrass beds enveloping the coastline of south Florida. Note that this is about 10% of the total area of seagrass coverage globally as estimated from totaling the mapped areas of seagrasses. Over much of this area, seagrass beds occur intermixed with coral reefs and hardbottom habitats. Seagrasses also grow immediately seaward of the mangrove forests of Miami-Dade County and Florida Keys, but dark-colored water flowing out of the extensive mangrove forests of the southwest Florida coast limit the shoreward extension of seagrasses there. The mix of these important habitat types contributes to the productivity of the system as a whole, since animals that seek shelter in one habitat can hunt for food in another.



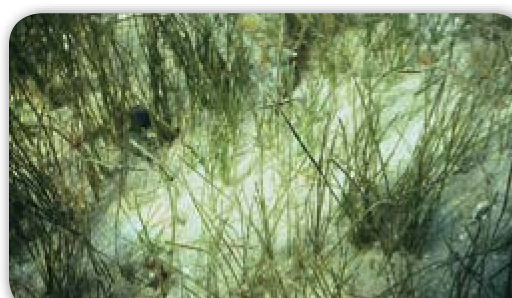
Adapted from Fourqurean et al. (2002)

The areal extent of seagrass distribution in south Florida is the largest documented seagrass bed on Earth.

The seagrass beds of south Florida are diverse. In the low light environments of the Southwest Florida Shelf, there are over 7000 km^2 (700 mi^2) of seagrass beds comprised of paddle grass (*Halophila decipiens*), a small (less than 2 centimeters [0.8 inches] tall), fast growing annual seagrass that is rarely seen by people, but is very important as the base of the food web. Closer to shore, where more light reaches the seafloor, salinity is relatively stable and there is an ample supply of plant nutrients, dense canopies of spaghetti-like manatee grass (*Syringodium filiforme*) rise over 1 m (3 ft) off the bottom. In more estuarine areas, where salinity can be variable and nutrient availability can be higher, seagrass beds can be dominated by the thin-leaved species shoal grass (*Halodule wrightii*) and widgeon grass (*Ruppia maritima*).

But, much of the south Florida region is characterized by relatively stable salinity, clear water and low supply of plant nutrients where turtle grass (*Thalassia testudinum*) predominates.

Because of the economic and ecological importance of the coastal regions of south Florida and the well-developed science and management infrastructure in the United States, the distribution of the seagrass resources of south Florida are very well known compared to many other regions of the world. The documented extent of the seagrasses in south Florida rank them as the most extensive seagrass ecosystem in the world, but it is almost certain that there are other large seagrass ecosystems in regions without the economic incentive or scientific infrastructure necessary to document their spatial extent. Understudied locales, such as the islands of the Indo-Pacific and the extensive offshore banks of the Caribbean, may prove to have seagrass beds that rival those of south Florida in areal extent.



T.A. Frankovich - FIU

FDEP

Different types of seagrass beds are found in south Florida. Shoal grass is a pioneer species that rapidly colonizes disturbed substrates (top). A large dense bed of manatee grass occurs just north of Marathon, Middle Keys, Florida (bottom).

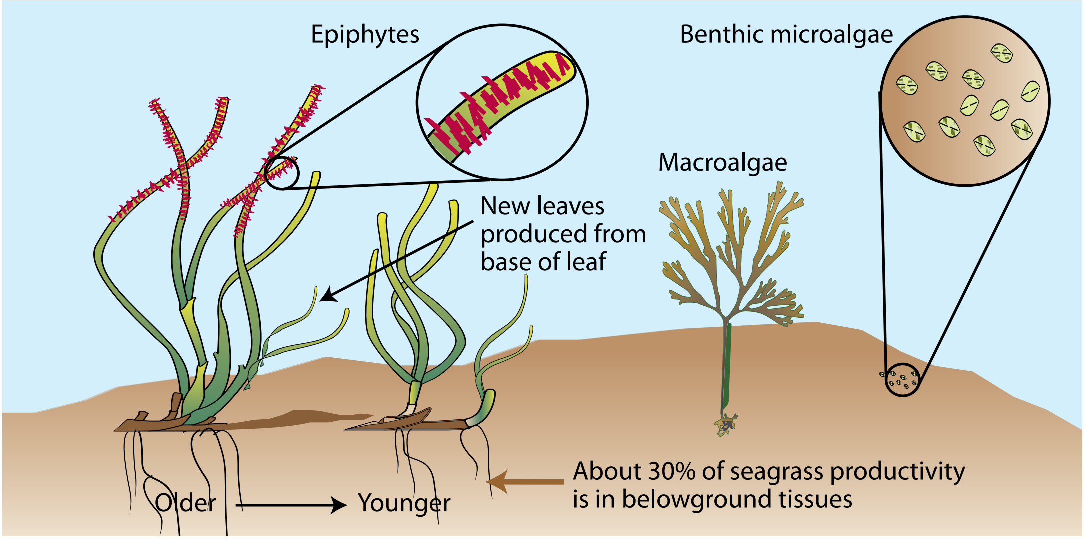
Seagrasses are one of the most productive plant communities on Earth

James W. Fourqurean

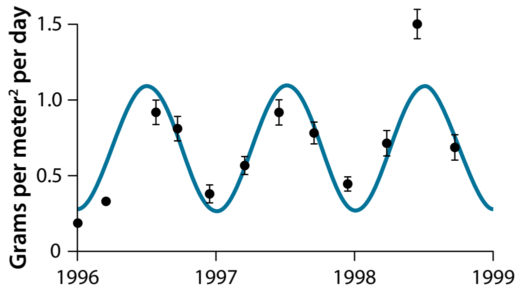
Seagrasses are among the most productive plant communities on Earth, generating as much as 18 grams of dry organic matter per square meter per day (g/m²/d). However, not all seagrass beds are equally productive; the global average seagrass productivity is estimated to be 2.7 g/m²/d. Even this mean value is higher than the mean productivity of cultivated cropland, which is 1.8 g/m²/d.

The organic matter that is produced by seagrasses and other primary producers found in the seagrass ecosystem, such as seaweeds, epiphytes on seagrass blades, and single celled algae in the sediment and water, serve as the base of the food chain of the coastal marine animal communities in south Florida. Some of the seagrass leaves are eaten by herbivorous animals, such as manatees and green sea turtles. However, much more of that biomass is shed from the growing plants, becomes colonized by bacteria and fungi, and becomes the detritus that many other animals consume. A portion of the net productivity is directed toward production of roots and rhizomes that stabilize the sands and muds in which they are growing. Belowground biomass also contributes to the detritus-based food web.

There is a broad range of rates of seagrass productivity in south Florida, largely because of the variable environments found in the seagrass beds of the region. Plants require light, water, and mineral nutrients to grow. Water is not a problem for seagrasses, as they grow completely submerged. The other two requirements, though, are often available in an inverse proportion; that is, when nutrient supply is high, water clarity is low and therefore light availability is low. In contrast, in clear water the nutrient supply is low and light availability is high. This relationship means that in most cases, the productivity of seagrasses is limited by either light or by the availability of nutrients.



Primary productivity of seagrass beds includes aboveground production of shoots and leaves and belowground production of roots and rhizomes. Other primary producers in seagrass beds include epiphytes on seagrass blades, macroalgae, and microalgae.



Adapted from Fourqurean et al. (2001)

Seasonality of productivity of seagrass leaves in south Florida. Summertime maximums are about twice as high as the annual average.

Since 1995, the productivity of turtle grass leaves has been measured at 35 monitoring sites in south Florida. Mean yearly productivity ranges between 0.05 – 3.29 $g/m^2/d$. In addition to leaf production, since about 30% of the total productivity of turtle grass goes into building plant parts other than leaves, the total productivity of turtle grass plants ranges between 0.07 – 4.7 $g/m^2/d$. The productivity of other plants in the seagrass bed can contribute as much production as the seagrasses themselves, making the estimate of the range in yearly average primary productivity of the entire seagrass bed community to be 0.14 – 9.4 $g/m^2/d$, or as much as five times the productivity as the average cultivated cropland.

J.W. Fourqurean - FIU

Benthic macroalgae contribute to the total primary productivity of seagrass beds.

Despite the tropical-subtropical climate of south Florida, productivity is markedly seasonal; summertime maximum rates of leaf production are about double the annual average rate, and winter rates are about half of the annual average. Production slows in the winter because both temperature and light availability decrease. The biomass of seaweeds and epiphytes increases in south Florida seagrass beds in the winter, suggesting that they are more important to the total ecosystem primary production when the seagrass growth slows.

R.L.H. Pavon - seeturtle.org

The green turtle changes from being an omnivore as a juvenile to a herbivore feeding primarily on seagrass leaves as an adult.

Seagrasses are important in the global cycling of carbon because of their wide distribution and their high rates of productivity. Dense seagrass beds fix more carbon than is respired in the beds, making them an important sink for carbon on a global scale. It is estimated that seagrass beds remove between 75 – 183 million metric tons (83 – 202 tons) of CO_2 per year from the global carbon budget based on the net growth of seagrasses. Further, seagrasses cause other organic particles to settle and become trapped in the sediments, bringing the estimates of total trapping of CO_2 of these highly productive systems to 175 – 409 million metric tons (193 – 451 tons) per year on a global scale.

Seagrasses are important to humans

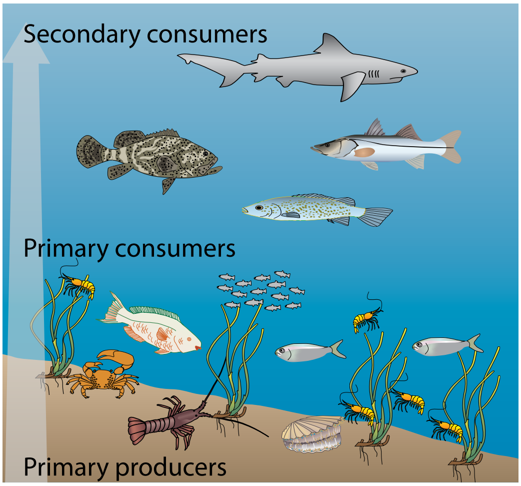
Michael J. Durako

Seagrasses are very productive and the amount of plant material that they produce in a year (i.e., biomass) is higher than that of cultivated rice or corn. Many animals eat seagrass directly, such as turtles, parrotfish, and manatees. Many species that utilize seagrass beds for food and shelter have recreational and commercial importance, such as snapper, grouper, speckled trout, redfish, scallops, spiny lobster, shrimp, stone crabs and blue crabs. In addition, seagrass beds provide food and shelter for most of the organisms that are fed upon by recreational and commercial species of fish and shellfish. Thus, they are a very important component of the coastal food chain.

Seagrasses are important in stabilizing shorelines with their extensive root and rhizome systems. They also function to improve water quality by taking up nutrients from the water and sediments. Seagrasses are often found close to shore in shallow water. Because of increasing population growth in coastal areas, seagrass beds are being threatened worldwide by eutrophication (i.e., adding nutrients to the water) due to poor sewage and stormwater treatment practices, dredging operations, sedimentation, and disruption of food chains due to overfishing. In south Florida, as well as many other coastal areas, seagrasses found in shallow waters are being damaged by propeller scarring from boat traffic in inappropriate areas. Approximately 70,000 hectares (173,000 acres) of seagrass beds in Florida are scarred and natural recovery of severely scarred beds is very slow or impossible due to changes in hydrology that inhibit reestablishment of the grass.

Some human uses of seagrasses

- Insulation for thermal and sound proofing (fiberglass substitute).
- Roofing for thatch roofs in United Kingdom and other European countries.
- Stuffing in pillows, mattresses, and upholstery.
- Packing material for the export of blue crabs and other products.
- Fibers used to make coir mats and rugs.
- Stock feed and mulch.
- Substitute for cotton in manufacture of nitrocellulose (flash paper).
- Pharmaceuticals
- Food: for example, the Seri Indians in Mexico use eelgrass seed as food.



A simplified seagrass food web showing some commercially important components.

Turtle grass is the main habitat for bay scallops in Florida.

Seagrasses provide valuable ecosystem goods and services

Alicia Farrer

What are ecosystem goods and services?

A service can be defined as providing things that are useful. Ecosystem services are functions that contribute to human welfare and help sustain the biosphere, such as the maintenance of water quality. Goods are things that have utility, such as harvestable fish. Human civilization depends on healthy ecosystems and the goods and services they provide. Many of these services are renewable, but many are irreplaceable.

South Florida and the Florida Keys are a world-class diving and fishing destination. Many of the fish that are found on the coral reefs in the daytime spend their nights foraging in the nearby seagrass beds. Seagrass beds also support a multimillion dollar recreational fishery including shallow water fishing for bonefish, tarpon, speckled trout, redfish, snook, and gray snapper.

Many commercial fishery species rely on seagrass beds as habitat during some part of their life cycle, including pink shrimp, spiny lobster, snapper, and stone crab. The estimated total value for Monroe County in 2006 for six seagrass-dependent species totaled approximately $25.8 million.

A. Massey - FKNMS

South Florida is a world-class fishing destination which attracts recreational fishers from all over the world. The shallow water fishing, or "flats fishing" industry relies on healthy seagrass habitats to provide a viable fishery which generates a significant source of income for south Florida.

NOAA

Blue tangs, a common coral reef fish species, regularly feed on adjacent seagrass beds.

Seagrasses provide many valuable ecosystem services, including:

- Providing habitat and nursery areas for many commercially and recreationally important fish and shellfish species (e.g., shrimp, crabs, lobster).
- Improving water quality by reducing turbidity and nutrients.
- Stabilizing sediments with roots and rhizomes.
- Providing coastal protection by dissipating wave and current energy.
- Providing recreational opportunities.

How is the value of an ecosystem determined?

Estimates of ecosystem goods and services are made by adding the known values that are provided to and by societies. It has been estimated that the value of all goods and services that natural ecosystems on planet Earth provide to mankind is $33 trillion (1994 dollars) per year, a time when the Gross Domestic Product of Earth was worth $18 trillion. Seagrass beds are estimated to be worth $3.8 trillion per year. This high percentage of the total value of ecosystem services supports the need for wise conservation of our valuable seagrass resources.

Some animals feed on seagrasses

Thomas A. Frankovich

Many animals, including sea turtles, manatees, parrotfish, and queen conch, feed on seagrasses and seagrass detritus. A major feeding area for sea turtles is found just west of the Marquesas Keys where green sea turtles gather to feed on turtle grass and manatee grass. Green sea turtles graze selectively on seagrasses, discarding the oldest leaves and eating only the youngest leaves that have higher nutritional value. They graze within specific plots and maintain areas that contain only new seagrass growth. These areas are lighter in color when viewed from the surface of the water, and resemble a recently mowed lawn from below the water surface.

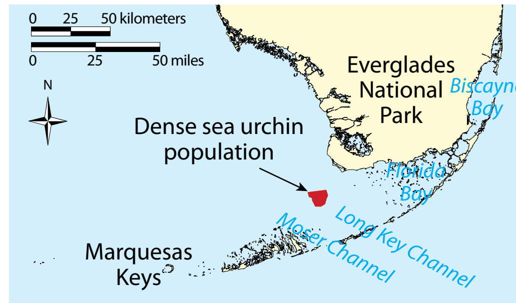
T. Noyes

Green sea turtle feeding in a seagrass grazing plot.

A population explosion of sea urchins

Animals that feed directly on seagrasses can dramatically impact the ecosystem. In August 1997, a commercial fisherman directed scientists to an unusually large abundance of the sea urchin (*Lytechinus variegatus*) located about 16.1 kilometers (10 miles) north of Marathon, Florida in an area known as the "Sluiceway" in Florida Bay.

Lytechinus feeds on seagrasses and algae and the population explosion



Location of dense sea urchin population in manatee seagrass bed in Florida Bay.

occurred in an area characterized by a dense and healthy stand of manatee grass (*Syringodium filiforme*). In less than a year, urchin densities increased from less than one urchin per square meter to over 170 urchins per square meter. They were stacked on top of each other!

During this time period, the urchins decimated over 81 hectares (200 acres) of seagrass, eating almost a hectare of seagrass per day. Urchin densities then declined to previous levels and the seagrass has proven to be very resilient and has recovered. Similar population explosions of sea urchins have occurred in other areas, and the reasons for these occurrences remain unknown.

C Rose - Seagrass Ecosystem Research Laboratory FIU

Sea urchin population explosion in manatee seagrass bed in Florida Bay. Density of urchins was over 170 individuals per square meter (1997 – 1998).

Seagrass meadows provide important habitat and support complex food webs

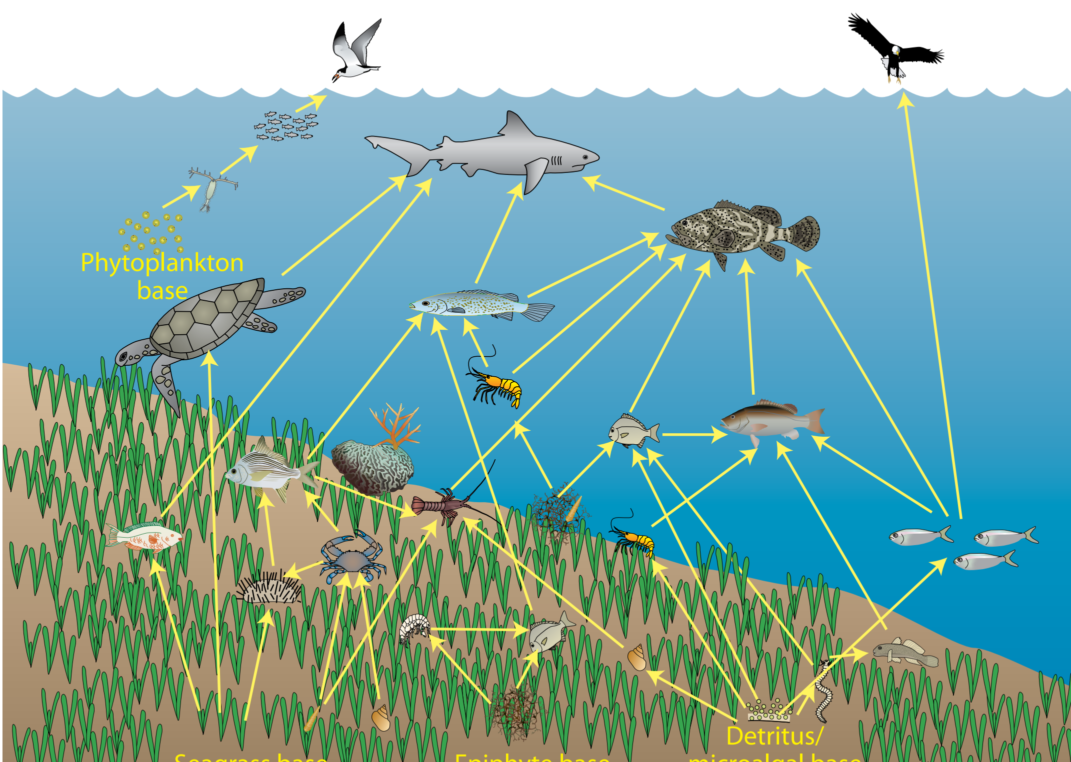
Thomas A. Frankovich

Seagrass meadows provide a complex, three-dimensional habitat for over 500 species of vertebrates and invertebrates. Most seagrass meadow food webs are a mix of primary producers, herbivores, carnivores, and detritivores. The base of marine food webs are the primary producers and consist of microalgae, macroalgae, seagrasses, and some bacteria. The microalgae and bacteria are eaten by herbivores (e.g., snails, shrimp, small fish), which are eaten by larger animals, which in turn are eaten by top level carnivores. The importance of the food web pathways is variable throughout the Florida Keys and Florida Bay, as well as seasonally. For example, shallow seagrass meadows in Florida Bay are predominantly a seagrass detritus or benthic microalgae-based food web.


T.A. Frankovich - FIU

A view into the complex, three-dimensional habitats within a turtle grass meadow in Florida Bay.

Seagrass beds located in deeper waters with higher salinity have abundant herbivores and the food web is more directly seagrass-based. Algal-epiphyte based food webs and phytoplankton-based food webs are common in nutrient rich areas where epiphytes and phytoplankton can outcompete seagrasses.



South Florida seagrass meadows support complex food webs.

Epiphytes are vital and often overlooked components of seagrass communities

Thomas A. Frankovich

Epiphytes are organisms, both plant and animal, as well as associated sediment and detritus, that are attached to the surfaces of plants. Seagrass epiphyte communities are often quite different from one another. Seagrass epiphytes found in areas of strong currents, such as oceanside back reef environments, predominantly consist of encrusting coralline red algae that forms whitish-pink crusts on the seagrass leaves.


T.A. Frankovich - FIU

Coralline red algae epiphytes on a turtle grass leaf found in high energy back reef habitat.

Within calmer waters, such as the interior of Florida Bay, epiphyte communities usually consist of a thin, golden film of microscopic diatoms. During prolonged wind events associated with periodic wintertime cold fronts, these epiphytic diatom communities often turn white when light-colored carbonate sediments are stirred up from the bottom and are trapped within the sticky epiphyte film.

Epiphytes are vital components of the seagrass ecosystem and form the basis of many food webs. Diatom and algal epiphytes are consumed by many species, including amphipods, shrimp, snails, and pinfish. Larger predators, including stone crabs, lobsters, seatrout, and other game fish then consume the epiphyte grazers.


T.A. Frankovich - FIU

There are thousands of known species of epiphytic diatoms. They form a golden film on seagrass blades.

Too much epiphyte accumulation is detrimental to seagrasses. Globally, epiphytes along with phytoplankton blooms are known causes of seagrass declines. Increased nutrients often fuel epiphyte and phytoplankton blooms. Increased shading, brought about by phytoplankton and increased epiphyte levels, may not allow enough light to maintain seagrass growth.


T.A. Frankovich - FIU

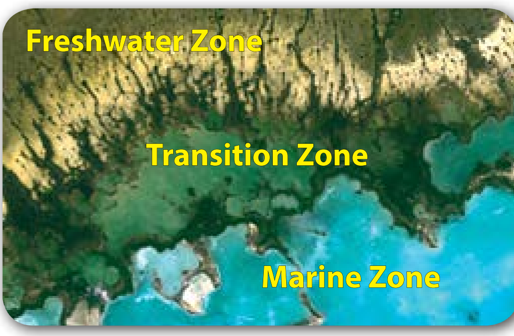
The chestnut turban snail feeds on epiphytic diatoms on seagrass leaves.

In south Florida, excess epiphyte accumulation is common near bird rookeries and roosting islands. Colonies of cormorants, pelicans, and frigate birds concentrate guano on several small mangrove islands in the Keys. High nutrient concentrations are leached from the islands to surrounding waters and result in a proliferation of epiphytes on nearby seagrasses. The increased epiphyte loading often results in complete loss of seagrasses in the area immediately surrounding the island, forming a characteristic halo of bare sediment. The effect of these bird islands on seagrass meadows is restricted to a few locations and is limited to about a hundred meters off the shoreline of bird rookeries.

Seagrass distribution and environmental stress: The delicate ecological balance

Marguerite Koch

Seagrass distribution in south Florida starts at the freshwater-marine transition zone between land and sea. In Florida Bay, this Transition Zone is represented by mangrove-lined tidal creeks that extend into the Freshwater Zone, and includes interior lakes and bays. Here a delicate ecological balance is required to support healthy seagrasses that in turn provide a diverse wildlife habitat.



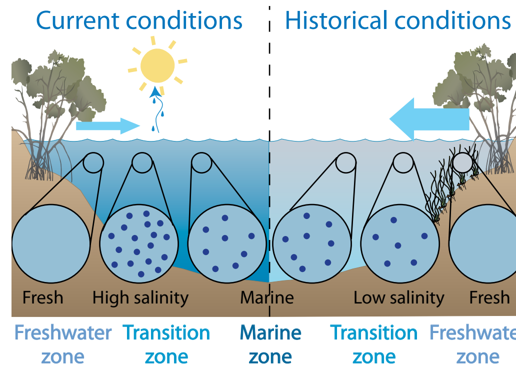
Google Earth with modifications by M. Koch

From top to bottom: Freshwater (tan), Transition (greenish) and Marine (blue) Zones in Florida Bay.

Widgeon grass (*Ruppia maritima*) is an important Transition Zone seagrass that provides habitat and feeding areas for fish, wading birds like the roseate spoonbill, waterfowl, manatees, sharks, alligators and other wildlife. Widgeon grass is very salt tolerant, surviving in water with a salinity of greater than twice seawater; but it also lives in freshwater.

deskpictures.com

Roseate spoonbills forage on fish supported by wigeon grass and other benthic plants in the Everglades transitional zone.



Current and historical hydrological conditions of the zones in Florida Bay. Drainage alterations reduced the historical freshwater flow to the Transition Zone. Currently, salinity rapidly changes from freshwater during rain events to abnormally high salinity during dry periods resulting in loss of seagrasses. A major feature of the Comprehensive Everglades Restoration Plan is to restore greater freshwater flow.

Historically, during times when freshwater flows into the Everglades were higher, the Transition Zone had lower salinity and widgeon grass was more dominant. Drainage projects throughout south Florida have modified salinity patterns in the Transition Zone. Currently, salinity rapidly changes to freshwater during rain events and to abnormally high salinity due to solar-driven evaporation during dry periods. These extremes often lead to seagrass die-offs in the Transition Zone and poor habitat and water quality.

In the Marine Zone of Florida, Biscayne and other bays and coastal areas of south Florida, the seagrass community is primarily represented by turtle grass (*Thalassia testudinum*), manatee grass (*Syringodium filiforme*), shoal grass (*Halodule wrightii*), and a few species of paddle grass (*Halophila*). Dominance by any individual seagrass species in the Marine Zone is dependent on several factors: 1) salinity and temperature along the coastlines; 2) nutrient availability in the water and sediments; 3) the depth and quantity of light reaching the plants; and, 4) frequency of disturbances.

Salinity and temperature

Turtle grass and shoal grass are tolerant of high salinity (60 parts per thousand), when salinity increases slowly, and high temperatures (36°C [97°F]), but only for short durations. Seagrasses adapt to short-term stresses by producing "protective" biochemical compounds in their tissues. Over the long-term, seagrasses can change morphology (e.g., narrower leaf widths) and express genes that promote resilience to environmental stresses. Gene expression over long time scales produces local seagrass populations with unique genetic fingerprints.

Nutrients and oxygen

Nutrients can be added to coastal waters and sediments from a variety of sources, such as bird guano, upwelling of groundwater, and land runoff. When high concentrations of nutrients are available in the water, shoal grass can grow rapidly and predominate, particularly in disturbed areas. Turtle grass dominates in the majority of estuaries and coastal zones of south Florida with low nutrients in the water because it has deeply penetrating roots that are able to "mine" the nutrients stored in sediments.

Although nutrients in sediments help seagrasses grow, when nutrients in the sediment are excessively high, seagrass plants can get very large and produce many shoots in a small area. As the plants die, the biomass builds up in the sediment. In some coastal areas, high seagrass shoot density and biomass build up destabilizes the ecology of the seagrass ecosystem in several ways:

- Seagrass shoots can become too crowded to provide optimal larval and juvenile fish/shellfish habitat.
- Large amounts of plant biomass lead to high oxygen consumption at night for respiration, resulting in low early morning oxygen levels or hypoxic conditions. Hypoxia can cause seagrass mortality and degrade the seagrass habitat.

M. Koch - FAU

Buchanan Bank seagrass die-off in Florida Bay, fall 2004, showing 50% mortality of turtle grass shoots.

- Under low oxygen conditions, sediment toxins (e.g., hydrogen sulfide) can accumulate and cause plant and animal toxicity.

Nutrients in the sediments from the Gulf of Mexico and other sources have allowed turtle grass to reach high densities in western Florida Bay. In the fall, short day lengths reduce the daily oxygen production from photosynthesis and increase total daily oxygen demand by extending darkness when no oxygen is produced. The imbalance between lower oxygen production and more oxygen consumption results in internal plant hypoxia. This plant hypoxic condition has been hypothesized to cause seagrass mortality (die-off) in Florida Bay and other regions of the world experiencing chronic nutrient enrichment. When seagrasses die their nutrients feed phytoplankton, which can lead to secondary seagrass mortality from light limitation.

Light

Turbidity, including particulates of phytoplankton and colored dissolved organic matter in the water column, reduce light availability to seagrass. Shading by phytoplankton can cause seagrass mortality or limit the depth that seagrass can live. Some seagrass species with high biomass, such as turtle grass, require more light to support their tissue oxygen demands. Turtle and shoal grass grow best where at least 20% of the surface light reaches the bottom. Some seagrass species with low biomass, such as paddle grass, are adapted to low light and can live at depths of 30.5 meters (100 feet).

Seagrasses are sentinels of water quality

James W. Fourqurean

Seagrasses can be viewed as "coastal canaries" that grow and monitor the marine environment and give warnings before the environment deteriorates and affects the services coastal ecosystems provide to human populations. Seagrasses grow rooted in place and are sensitive to environmental conditions. They are long-lived, and therefore integrate environmental conditions over a long time span. Because some seagrasses can produce tissues that can persist in the environment for decades, they not only provide a record of current conditions, but they can also provide evidence of long-term changes in the ecosystem. Intelligent measurements of seagrass metrics can yield a wealth of information about the health of the plants, as well as the status of the ecosystems they support.

Seagrasses as canaries

During the 19th century, caged canaries were kept in working coal mines as biological sentinels. The fast metabolism of the canary made it more sensitive than the human miners to poor environmental conditions in the mine. When the canary stopped singing, it gave the miners a warning that the atmosphere in the mine could no longer support them, signaling a need to evacuate the mine. Luckily for the canaries, modern, sensitive instruments were developed in the early 20th century to monitor the environment in a mine without requiring a canary.

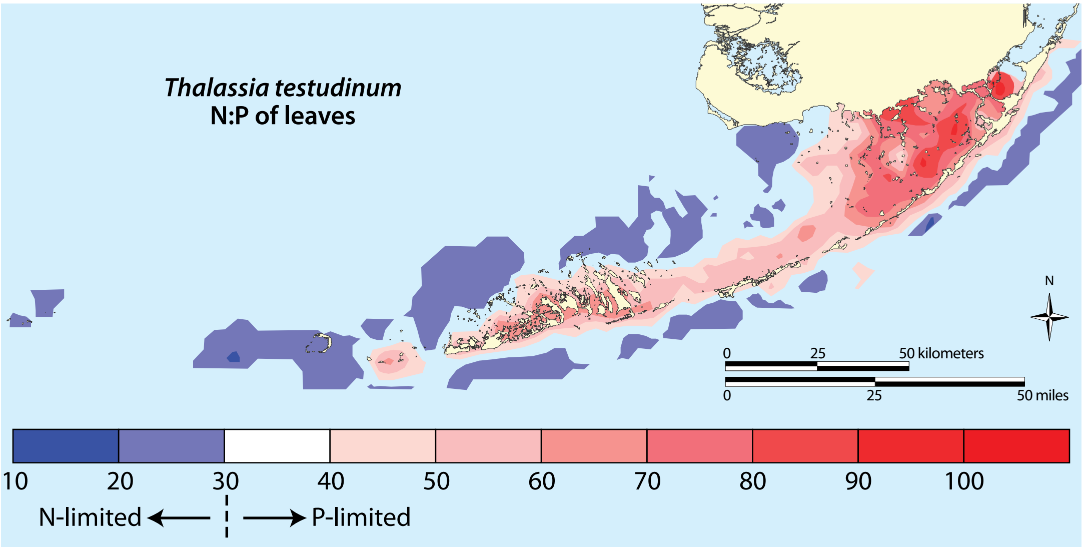
Seagrasses require high light levels, which is a consequence of living in anoxic sediments, and they are subject to an overgrowth of epiphytes on their leaves. As a general rule of thumb, survival of seagrasses in south Florida requires that about 10% of the sun light energy that enters the water reaches them. The light requirement of seagrasses is greater than many other plants that live in low light environments. For example, plants that live in the understory of tropical rainforests, oceanic phytoplankton, and most seaweeds require as little as 1% of the energy from the sun to thrive. There are exceptions to the 10% rule of thumb for seagrasses and different seagrass species have different light requirements. For example, paddle grass (*Halophila decipiens*) is widely distributed on the Southwest Florida Shelf and in the deeper water, as deep as 30.5 meters (100 feet) between the Marquesas Islands and the Dry Tortugas, where as little as 5% of the energy from the sun reaches the bottom. The other common seagrasses of south Florida all have substantially higher light requirements than paddle grass. Some seagrass beds that are particularly stressed by low oxygen concentrations in sediments or high epiphyte loads can require more than 10% of the surface irradiance. Because the light requirements of seagrasses are well understood, seagrasses can be thought of as "integrating light meters" and provide indices to reflect long-term averages of water quality.

The amount of light penetrating water is directly related to the quality of the water. In very clear water of the open ocean, 10% of the energy from the sun can reach as deep as 30.5 m (100 ft), but in highly turbid, polluted estuaries, 10% of the light can penetrate only a few centimeters deep. Decreases in the maximum depth of seagrasses in an area are an indicator that water quality has deteriorated.

However, long before seagrasses succumb to decreasing water quality, other aspects of seagrass plants can be used to indicate the status and trends of water quality. In south Florida, the ratios of essential chemical elements in seagrass leaves provides such an indicator. The ratios of the most common of these elements required for balanced growth of phytoplankton is called the Redfield Ratio, which is 106 atoms of carbon for every 16 atoms of nitrogen and every single atom of phosphorus (or, in chemical shorthand, C:N:P = 106:16:1). Seagrasses have different structural characteristics than phytoplankton; the average C:N:P for balanced seagrass growth is 550:30:1. Deviations of measured elemental content from these ratios have long been used to infer shortages of elemental supply for supporting plant growth.

A N:P ratio of less than 30:1 in seagrass leaves indicates that the plants do not receive enough nitrogen for optimal growth, while N:P greater than 30:1 indicates a phosphorus deficiency. The N:P in the leaves of turtle grass in south Florida clearly shows that, on average, phosphorus is in short supply in Florida Bay and close to shore in the Keys, but further offshore near the reef tract, there is ample phosphorus but a shortage of nitrogen. This spatial pattern has important implications for wastewater and stormwater management in the Florida Keys. Releases of phosphorus close to shore will fertilize the seagrass beds and cause them to change in undesirable ways, but nitrogen releases will have no effect on the seagrasses close to shore since they already have more nitrogen than they can assimilate. However, nitrogen waste released close to shore could be transported offshore where N is in short supply and have an effect on seagrass beds many miles away from the pollution source without affecting the nearshore seagrass beds.

Because the amount of nitrogen and phosphorus in plants is a function of both the supply of the element from the environment and the demand for the element to build new plant biomass, changes in either the supply rate of nutrients or the photosynthetic rate of the plant can change elemental ratios. Under low light conditions, the demand for nutrients for growth can be met by a smaller supply rate of nutrients than under high light conditions. Because of this effect, a decrease in light reaching the bottom, a common symptom of pollution, will change the N:P of seagrasses and other bottom plants. Under very low light conditions, growth is slow enough so that both N and P are available in quantities high enough to make biomass with

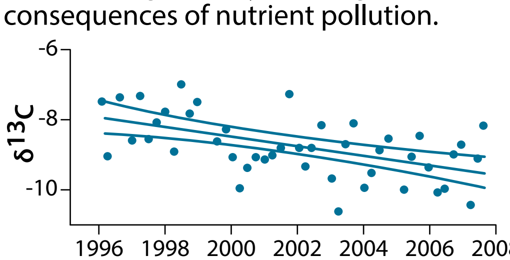


Spatial pattern of nitrogen:phosphorus in turtle grass leaves in the Florida Keys National Marine Sanctuary and Florida Bay. Red means phosphorus is limiting; purple means nitrogen is limiting.

optimal concentrations and the N:P in seagrass leaves will be about 30:1. Thus, the N:P of seagrasses can be used as an indicator of change in water quality over time at a site. At many locations in the Florida Keys, the N:P ratios in seagrass tissues have been trending towards 30:1 since 1995, indicating that less light is reaching the bottom in 2009 than reached the bottom in 1995. The most simple mechanism to explain these trends is a subtle decrease in water quality over this time frame. The decrease in water clarity has not been severe enough to cause the loss of seagrass beds—yet.

A decrease in light availability to seagrass leaves is also demonstrated by measurements of isotopic ratios of the element carbon in seagrass leaves. Photosynthesis is a process that strongly favors the uptake of ^{12}C over ^{13}C. So, a plant that is fixing CO_2 during photosynthesis will become enriched in ^{12}C relative to the amount of that isotope in the source pool of CO_2. However, if all of the available CO_2 is used up by photosynthesis, the carbon fixed by the plant contains all of the molecules in the original source pool, no matter what the isotope of carbon they contained. So, a plant in a low light environment will have more ^{12}C and less ^{13}C than the CO_2 pool, but one in a high light environment will have an identical ^{13}C: ^{12}C ratio as the source pool. Geochemists use a shorthand called the "delta value" to represent the ratios of stable isotopes. The delta value ($\delta^{13}C$) of plants from low light environments is lower than that of plants from a high light environment. Hence, the $\delta^{13}C$ of seagrasses provides another way to interpret light availability to seagrasses. At many sites in south Florida, the $\delta^{13}C$ of seagrasses has been decreasing since 1995, suggesting that less light is available in 2009 than in 1995.

Careful monitoring of the elemental and isotopic composition of seagrasses across the south Florida seascape has been important in developing an understanding of the susceptibility of the ecosystem to nutrient pollution. Although the distribution of seagrasses has not changed from 1995 – 2009, the elemental and isotopic content data both suggest that less light is reaching the bottom today than in the 1990s across much of the region, and seagrasses may be providing an early warning of the dire consequences of nutrient pollution.



$\delta^{13}C$ has been decreasing in turtle grass leaves from 1995 – 2009, indicating that light availability has been decreasing.

A primer on stable isotope chemistry

Elements are determined by the number of protons in the nucleus of their atoms. But, an atom nucleus also contains neutrons in addition to protons. For many elements, the number of neutrons is variable, and the number of neutrons determines the form of the element to which that atom belongs. Atoms of an element with different numbers of neutrons are called "isotopes". Some isotopes are stable. For example, Carbon 12 is an isotope of carbon that has 6 protons and 6 neutrons in a nucleus (written as ^{12}C). ^{13}C is also a stable isotope of carbon with 6 protons and 7 neutrons. Some isotopes, however, are unstable, and when they deteriorate they emit radiation. Carbon with 6 protons and 8 neutrons is the radioactive ^{14}C isotope of carbon.

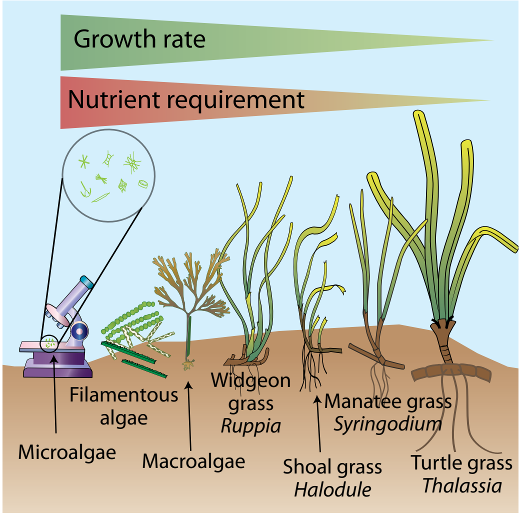
Stable isotopes of elements form identical molecules as other stable isotopes of the same element, but owing to their different masses, different stable isotopes react slightly differently. Because of this difference in reaction rate, biological and physical processes often favor one stable isotope of an element over another. This results in stable isotope signals in biological materials that can contain a wealth of information about the sources and processing of organic matter.

As nutrients change, so do marine plant species

James W. Fourqurean

All plants, including seagrasses, require light, water, and mineral nutrients, such as phosphorus and nitrogen, to grow. The required supply of nutrients for any plant population to grow is a function of the relative growth rate. Plants that grow quickly require high rates of nutrient supply, while plants that grow more slowly require a lower rate of supply. As a consequence, rapidly growing plants are found where nutrient supplies are high, and slow growing plants where nutrient supplies are low. High nutrient supplies are not necessarily bad for slow growing plants, but at high nutrient supply rates fast growing plants can overgrow and shade out the slow growers.

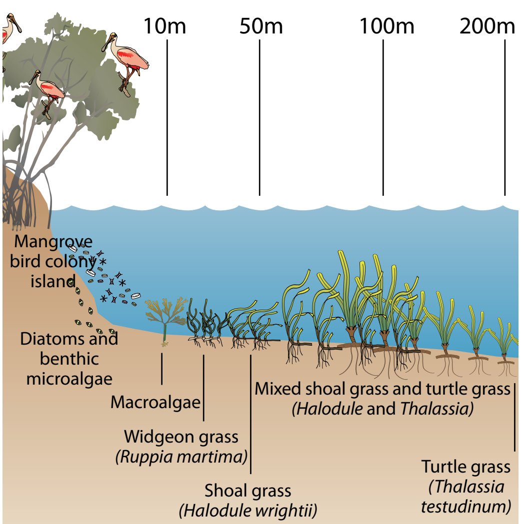
In general, the size of a plant is a good indicator of its relative growth rate, with smaller plants having higher growth rates. In seagrass beds in south Florida, the fastest growing plants are the single celled algae that live either in the water, in the sediments, or attached to hard surfaces, such as seagrass leaves. Filamentous algae that grow on surfaces grow slightly slower, followed by more complex macroalgaes, like the fleshy and calcareous seaweeds. Seagrasses grow even slower. Different species of seagrass have different growth rates and nutrient requirements. The narrow-bladed species widgeon grass (*Ruppia maritima*) and shoal grass (*Halodule wrightii*) grow faster than the spaghetti-like manatee grass (*Syringodium filiforme*) which in turn has a faster growth rate, and therefore higher nutrient requirements, than turtle grass (*Thalassia testudinum*). It is also possible, and is quite common in south Florida, that nutrient supplies can be so low as to constrain the growth of even the slowest growing species.



There is an inverse relationship between the size of plants and their growth rates. Small, microscopic algae living on sediments, in the water column, and attached to seagrass leaves have the highest growth rate and the highest nutrient requirements. Turtle grass has the slowest growth rate and predominates in nutrient-poor environments.

Evidence to support the relationship between growth rate and nutrient requirement come from both the distribution of seagrasses around natural nutrient "hot spots" in south Florida and from fertilization experiments. For example, the natural state of eastern Florida Bay is very low nutrient availability. However, on some of the mangrove islands in Florida Bay, there are large colonies of wading birds that hunt for food around the Bay. Those birds roost and nest on the islands, and bring food home to feed their young. Both adults and young defecate on the islands, causing natural point sources of nutrient supplies around these small islands. In response to this point source, nutrient availability is very high within a few meters of the islands and decreases with distance away from the mangrove shoreline. In response to this gradient, there are concentric halos of different plants growing on the bottom. Closest to the island, there is only a coating of microalgae covering the sediments. Further away from the island there is a macroalgae zone, followed by a halo of dense widgeon grass, a halo of dense shoal grass, then a zone of mixed shoal grass and dense turtle grass. Farther away still, outside the zone of influence of nutrients from the bird colony, turtle grass declines in density to very sparse coverage.

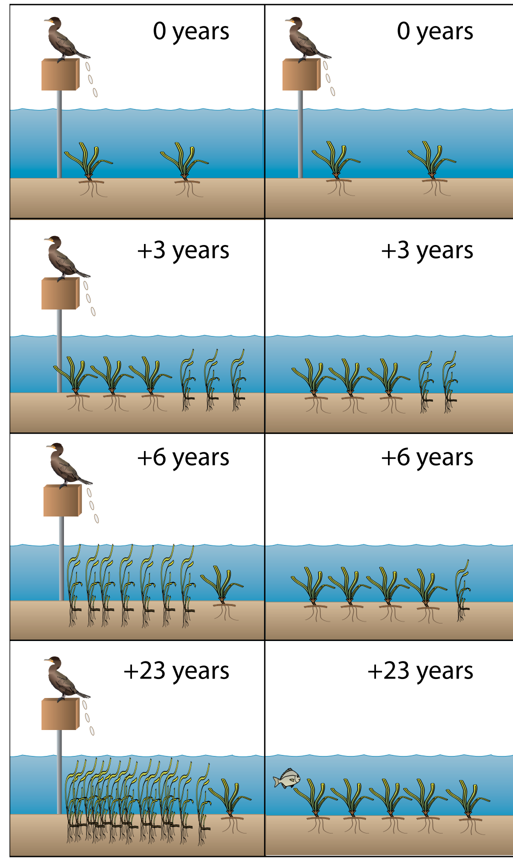
Fertilization experiments have confirmed that a change in nutrient supply first leads to a change in the density, and then the species composition, of seagrass beds in south Florida. In Florida Bay, fertilizing sparse turtle grass beds with phosphorus first results in an increase in the density of turtle grass; however, once shoal grass becomes established in the fertilized patches, it rapidly displaces the turtle grass. In the back reef environments of



Nutrient availability, which decreases as you move further offshore from mangrove islands with bird colonies, determines the location of algae and seagrass.

the Florida Keys, fertilization of sparse turtle grass beds with nitrogen also leads to an initial increase in the density of turtle grass, but soon the faster growing manatee grass becomes the dominant seagrass species.

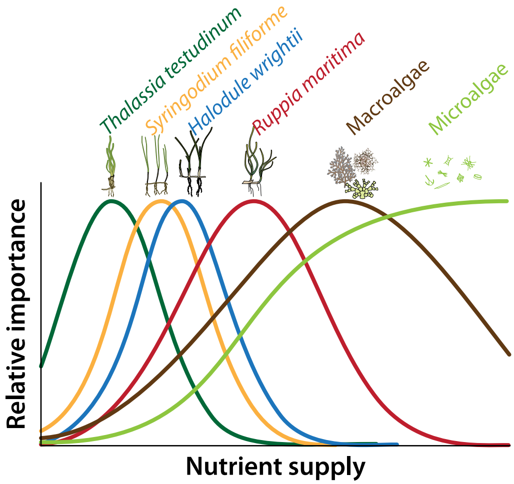
Less controlled experiments illustrate how the seagrass beds of the Florida Keys changed as the Keys became developed. Early developments relied on cesspools



Density and change in species of seagrasses in Florida Bay following fertilization after installation of bird roosting stakes in a turtle grass bed with sparse density (upper panels). Long-term fertilization (left column) resulted in a change to almost complete coverage of shoal grass 6 years after installation of the bird stakes. Shoal grass grows better than turtle grass in areas with higher nutrients and shoal grass continues to dominate the seagrass community around the bird stakes 23 years after the stakes were installed. Thus, continuous nutrient addition to seagrasses can change the long-term composition of the benthic community. Some bird stakes were removed 3 years after their installation (short-term fertilization; right column). By year 6, turtle grass again became the dominant seagrass and almost completely displaced (out competed) shoal grass under lower nutrient conditions. By year 23, the seagrass bed had reverted to almost exclusively turtle grass. Thus, the seagrass community can recover after a period of time to its original condition when the source of nutrients is removed. However, it takes several years to recover to its original condition because of the efficiency of seagrass systems in retaining and recycling nutrients.

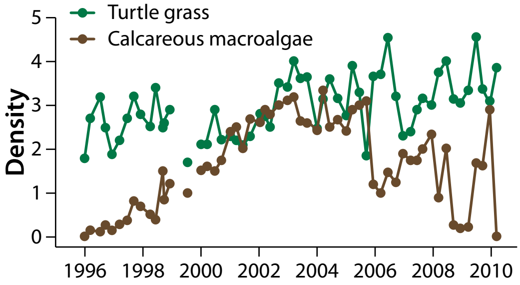
or septic tanks for wastewater "treatment." Neither provide nutrient removal in the rocky limestone substrate of the Keys. Thus, wastewater and stormwater nutrients emanating from the shoreline development resulted in the growth of lush seagrass beds immediately offshore of Key Largo.

This observation could be interpreted as a "good" thing because seagrass growth and coverage expanded. However, data from other observations and experiments temper this optimism.



This model illustrates how seagrass composition changes with nutrient supply.

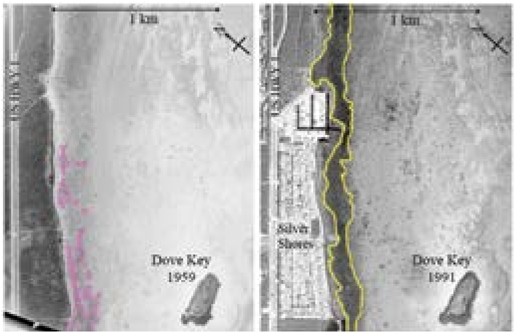
A model has been developed to illustrate how normally low nutrient seagrass beds of south Florida will change as nutrient availability changes. The model shows that seagrass beds composed of abundant turtle grass, the slowest growing species, become lush with increased nutrient conditions. But, as nutrient supply continues to increase, the species composition gradually changes as faster growing species replace slower growing ones. At highest nutrient levels, benthic seagrasses are replaced by macroalgae and microalgae. Loss of the seagrass component of the community will result in a dramatic change in community structure and function.



Density of turtle grass (green) and calcareous macroalgae (brown) at a monitoring station in the Florida Keys National Marine Sanctuary. Density of turtle grass was relatively stable from 1996 – 2009. Density of benthic macroalgae increased substantially from 1996 – 2006. The reason for the decrease in benthic macroalgae density in recent years is not known, but may be related to frequency of tropical storms.

Animal species dependent on seagrass for food and shelter (e.g., speckled trout) will be replaced by less desirable species (e.g., jellyfish).

The model predicts that the relative abundance of benthic plants at a site is an indicator of the current rate of nutrient supply. Changes in the relative abundance from slow growing to fast growing species at any site indicates an increase in nutrient supply. At many benthic monitoring sites in the Florida Keys, such shifts towards more fast growing species have been observed. Hopefully, improvements to wastewater and stormwater treatment and disposal will reverse this trend in species shift.



FDOT

Seagrass distribution along the shoreline of Key Largo near Dove Key in 1959 (left) and 1991 (right). Prior to development, seagrass coverage was sparse along the shoreline. However, by 1991 seagrass coverage and density increased substantially along the shoreline in response to nutrients emanating from development.

Seagrass Habitats

In 1987 a large area of turtle grass died in Florida Bay

Michael J. Durako

Seagrasses, primarily turtle grass (*Thalassia testudinum*), are the dominant biological community in Florida Bay, historically covering over 90% of the 180,000 hectares (445,000 acres) of subtidal mud banks and basins within the Bay. By comparison, mangrove islands cover only about 7% of the Bay. Seagrass abundance to a large extent determines public perception regarding the "health" of the coastal waters of Florida. Thus, changes in the distribution and abundance of seagrasses within Florida Bay have been perceived as a change in the health of the Bay.


M.J. Durako - UNCW

Turtle grass die-off in Johnson Key Basin showing dead leaves and shoots with lesions (brown markings) on leaves.

A widespread die-off of seagrasses within Florida Bay was first observed in 1987 by fishing guides who reported the occurrence of "potholes" in several basins. At the same time, widespread coral bleaching was observed along the Florida Keys Reef Tract. Extensive areas of turtle grass began dying rapidly in central and western Bay basins, and by 1990, almost 4,047 ha (10,000 ac) were completely lost and 23,876 ha (59,000 ac) were affected by the die-off.

Factors such as elevated water temperature (associated with an El Niño event), prolonged hypersalinity, and excessive seagrass biomass (due to lack of recent hurricanes), leading to increased respiratory demands, hypoxia and sulfide toxicity are some of the physiological stressors thought to have contributed to the die-off. The specific sequences of causative mechanisms responsible for initiating the die-off in Florida Bay have been proposed in a model.

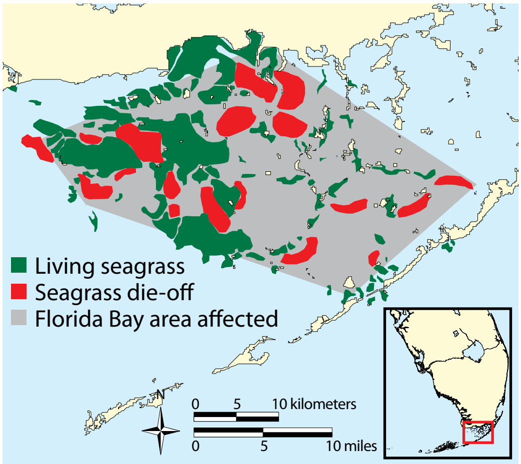
The patterns of loss of seagrasses in Florida Bay in the 1990s occurred in at least two phases. The first phase of the die-off occurred during the relatively hot, dry period of 1987 to early 1991 and appeared to affect only dense turtle grass beds. The second phase began during the fall of 1991 and was marked by widespread and chronic turbidity. The increase in turbidity was principally caused by microalgal blooms and resuspended sediments associated with


M.J. Durako - UNCW

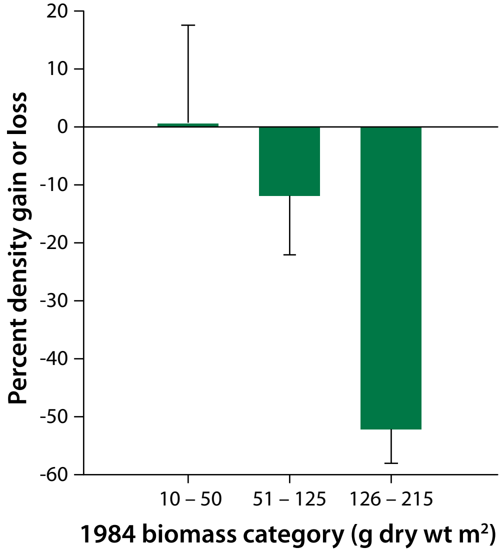
Aerial photograph of the Dump Keys in central Florida Bay surrounded by turbid greenish waters due to a *Synechococcus* (blue-green algae) bloom.

the loss of seagrasses on the western banks of the Bay, and it was most severe in the western and central Bay. The microalgal blooms, consisting largely of a *Synechococcus* cyanobacteria (blue-green algae), may have been initiated by the nutrients liberated from the die-off of seagrasses. Sponge mortality, changes in juvenile lobster population dynamics, and indications of cascading effects on plant and animal communities in adjacent systems (e.g., sea urchin population explosions and unbalanced growth of manatee grass in the waters of the Florida Keys National Marine Sanctuary southwest of Florida Bay) were also associated with the loss of seagrass communities within Florida Bay.

Comparisons of seagrass distributions in Florida Bay between 1984 – 1994 indicated that the chronically turbid regions exhibited the most significant losses of turtle grass. In contrast, the lower light adapted pioneer/disturbance species, shoal grass (*Halodule wrightii*), doubled in abundance across the Bay and increased up to 400% in the western basins, from 1995 – 1998. Recruitment and spread of another low light adapted and small-bodied seagrass, star grass (*Halophila engelmannii*), in the western basins indicated that a major community response resulting from die-off was a change to a more shade adapted seagrass community.



Map of seagrass die-off. Gray polygon shows general area of Florida Bay affected. Red shows areas along banks that exhibited most severe losses.



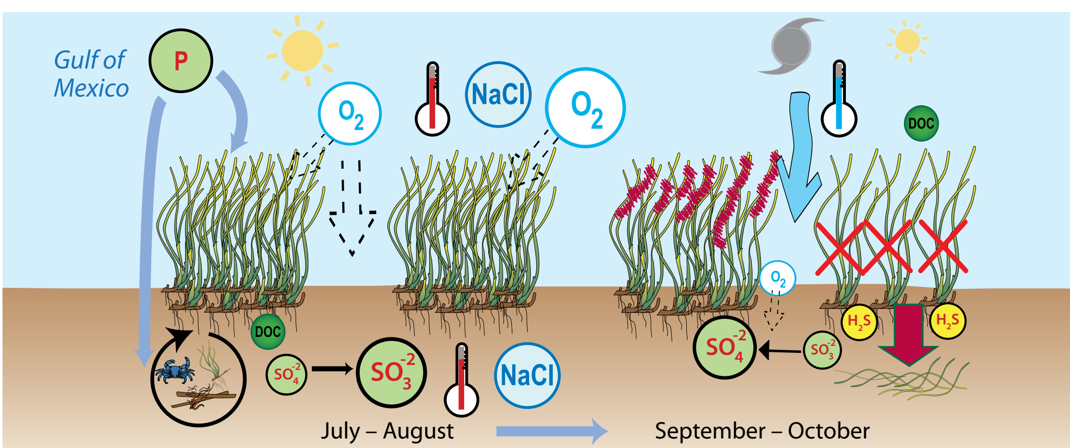
This graph shows that turtle grass beds with the highest density in 1984 (126 – 215 g/m^2) had the greatest loss (50%) after the die-off in 1994.

The spatial patterns of change from 1995 – 1998 suggested that the most perturbed environment was along the western Bay margin, bordering the open waters of the Gulf of Mexico. Since 1999, this area has become more stable with greatly improved water clarity. The waters of western Florida Bay form a hydrodynamic link between the Everglades and the coastal waters of the southwestern Florida peninsula/eastern Gulf of Mexico, to the north, and the Florida Keys Reef Tract and the Atlantic Ocean to the south. The seagrass communities of this region form an important buffer to the reef tract by intercepting the flow of water and reducing nutrient and particulate loads in the waters reaching the reef tract. Losses of seagrasses along this margin, coupled with the proposed increase in water flowing out of the Everglades, could result in greater fluxes of turbidity and nutrients out of Florida Bay and onto the reef tract.

A cascade of events causes seagrass die-off in Florida Bay

Marguerite Koch

Seagrass habitats are found in coastal estuaries and lagoons throughout tropical and temperate climates. They have high biological productivity, stabilize sediments, and provide habitat for diverse biological communities, including many species of commercial and recreational importance. It is alarming that there are a growing number of reports of large-scale seagrass die-off events worldwide. Die-off is defined as a sudden loss of the aboveground portion of seagrasses. Several factors have been proposed to cause large and small scale die-off events, including high nutrients, decreased light penetration, competition with macroalgae, high salinity (i.e., hypersalinity), temperature, and sulfide toxicity. In Florida Bay, seagrass die-off events as large as 4000 hectares (almost 10,000 acres) have been reported, and smaller scale mortality events occur annually. Field and laboratory studies by many scientists support the assumption that no individual stress factor has caused the seagrass mortality events in Florida Bay. The conceptual model presented below is based on studies and observations and consists of a sequential cascade of stressors that lead to seagrass die-off as observed in southwestern Florida Bay.

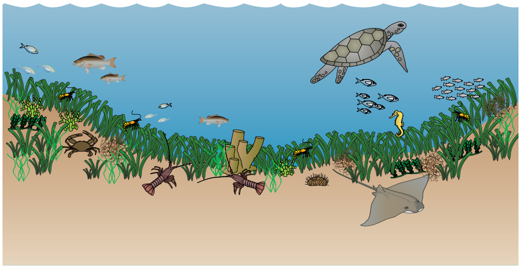


This model has been developed to explain the causes of seagrass die-off in Florida Bay and is based on a synthesis of field data and observations and mesocosm experiments. It shows a cascade of stressors that eventually lead to asphyxiation of seagrass that causes a die-off. The cascade of events is stimulated by phosphorus (P) enrichment from the Gulf of Mexico that leads to high summertime productivity and high oxygen consumption (O_2) in the system by both plants and sediment (sulfate reduction $SO_4^{-2} \rightarrow SO_3^{-2}$). Release of dissolved organic carbon (DOC) from the plants further stimulates sulfate reduction and accelerates oxygen demand by the rhizosphere (root system). During drought years in the summer, high temperature and hypersalinity (NaCl) increase the plants' requirements for oxygen in the water column. In the fall, day length shortens, temperatures cool, and plants produce less oxygen (O_2). The peak of the hurricane season in September introduces freshwater to the system, and epiphytes cover seagrasses. Nighttime hypoxia occurs at the sediment-water interface, creates an oxygen imbalance in the system, and results in plant asphyxiation and toxic sulfides (H_2S) accumulate in organic carbonate sediments that are low in iron. Plants die due to exposure to poisonous hydrogen sulfide. Although die-off can be extensive, seagrasses have been shown to recover. Live shoots are still present and those plants and new recruits can fill in open spaces in about 10 years. The increasing frequency and earlier seasonal occurences of die-off events are a recent concern.

Seagrass communities in Florida Bay changed after the die-off

Margaret O. Hall

Seagrass communities have historically dominated the bottom of Florida Bay, with turtle grass (*Thalassia testudinum*) being the most abundant species present. Extensive areas of turtle grass began to die rapidly during the summer of 1987, particularly in western portions of Florida Bay. This die-off followed a period of extended drought that caused high salinities in the Bay, and throughout the Bay the water was reported as "gin clear". By approximately 1990, the rate of die-off had slowed considerably, but it still occurs sporadically today in small areas of the Bay. During the period of extensive die-off, water clarity in Florida Bay remained clear and shoal grass (*Halodule wrightii*) began recolonizing the areas left bare from turtle grass mortality. Scientists and fishermen breathed a sigh of relief as the seagrass ecosystem seemed to be on its way to recovery.



Prior to 1987, water in Florida Bay was "gin clear" and the bottom was covered with dense seagrass meadows dominated by turtle grass.

But not so fast... In 1991, Florida Bay began suffering another substantial environmental insult, a widespread decline in water clarity. Decreased light penetration due to microalgal blooms and resuspended sediments in the water column, caused by loss of stabilizing seagrass, was most severe in western and central Florida Bay. Blooms were most likely fueled by nutrients released from the dying seagrasses and resuspended sediments. While die-off only affected turtle grass in Florida Bay, reduction of light availability affected all seagrass species. Shoal grass that had recolonized die-off patches of turtle grass was quickly lost, and by 1994, substantial reductions in the abundance of turtle grass, shoal grass, and manatee grass (*Syringodium testudinum*) occurred in regions of Florida Bay where light was most limited. Water clarity gradually improved during the second half of the 1990s, but damage caused by the blooms to sponges and other benthic life in the Bay will take a long time to recover.

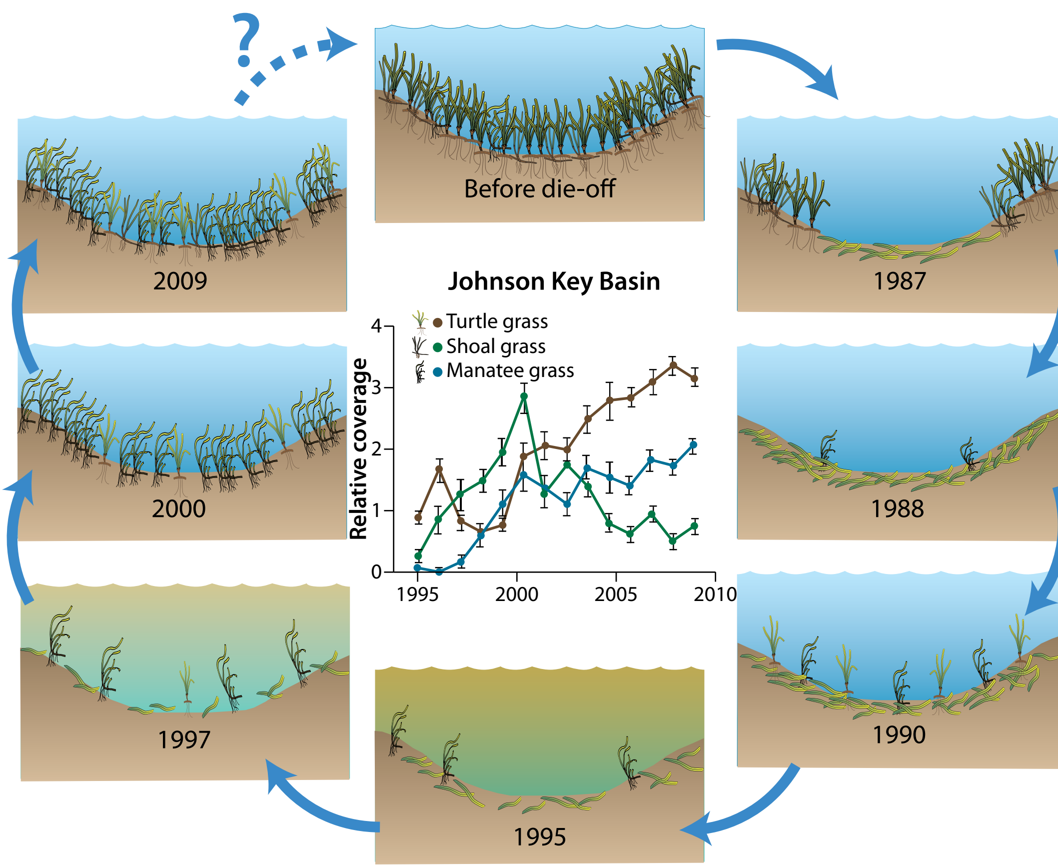
In 1995, the Florida Fish and Wildlife Conservation Commission Fisheries Habitat Assessment Program was established to document the status and trends of Florida Bay seagrass distribution, abundance, and species composition. Analyses of data collected from 1995 – 2009 revealed significant trends in seagrass density within several Florida Bay sampling locations that corresponded to changing water quality conditions, as well as predicted species successional patterns. The seagrass dynamics in Johnson Key Basin illustrate

FWC

Microalgal blooms in Florida Bay reduced water clarity and resulted in loss of recovering seagrasses. Blooms of blue-green algae also caused the death of loggerhead sponges throughout the Bay.

a representative sequence of events in western Florida Bay. When sampling was initiated in 1995, cover of all seagrass species was sparse, and water clarity was poor. Over time, water clarity improved, and the frequencies and densities of all seagrass species increased, but temporal patterns were quite different among species. Shoal grass, the fastest growing species, showed the most rapid response. Eventually the abundance of the longer-lived species, turtle grass and manatee grass, also began to increase. Density of shoal grass peaked in 2000, but has declined since then. Densities of turtle grass and manatee grass have continued to increase, and are exhibiting significant recovery in relative cover.

The changes in species abundance in Johnson Key Basin followed a secondary successional pattern typical for subtropical seagrass systems, and have resulted in a mixed-species community dominated by turtle grass. Comparing these temporal trends to Johnson Key Basin water quality data indicates that the seagrasses are responding to increasing light availability due to lower turbidity and lower chlorophyll in the water column. Hopefully, Florida Bay is on the road to recovery to a diverse mix of seagrass species.



Changes in seagrasses in Johnson Key Basin, western Florida Bay, were typical for the Bay. In 1987, die-off killed extensive areas of turtle grass, particularly in the western Bay. By 1990, the rate of die-off slowed and seagrasses were recovering. However, in 1991, phytoplankton blooms reduced water clarity in the Bay and caused substantial loss of all seagrass species. All seagrasses were sparse in 1995 and water clarity was poor due to suspended sediments from loss of seagrasses and increases in phytoplankton. Water clarity began improving in 1997, and shoal grass rapidly increased in abundance. Turtle grass and manatee grass responded more slowly which is consistent with the successional pattern for subtropical seagrasses. Today, there is a mixed community of seagrasses in Johnson Key Basin and other areas of the Bay.

Human activities damage seagrass habitats

Alicia Farrer

Threats to seagrasses include dredge and fill projects, degraded water quality, physical impacts by fishing gear, boat propellers and anchors, trampling, and shading.

Dredge and fill activities

Historically, dredging and filling of coastal areas has caused the most destructive and widespread impacts to seagrass beds in Florida. State (Florida Department of Environmental Protection) and federal (United States Army Corps of Engineers) permits are required for impacts to wetlands and seagrasses, however, neither program is a "protection" program and permits may be issued with compensatory mitigation. Unfortunately, many mitigation projects are not carried out or perform poorly and thus, do not replace losses.

Fishing gear

Lobster, crab, and fish traps can kill seagrasses by smothering and shading. Trawl nets used by fishermen also damage seagrasses by excavating or otherwise disturbing the bottom.

Dock construction

Structures built above and adjacent to seagrass beds that limit light availability can cause the loss of seagrass and other submerged vegetation. Some policies and best management practices are in place to attempt to minimize the impacts of docks by requiring construction methods that minimize damage, such as the height of the platform, spacing between boards, and dock location.

A. Farrer - FKNMS

An example of a trampled path through a seagrass bed. Trampled seagrasses recover slowly.

Propellers can severely damage seagrass beds.

Trampling

Repeatedly walking and/or standing on seagrasses can destroy seagrass blades and roots and eventually kill the seagrass. Research has demonstrated that seagrass beds recover slowly after being trampled; many trampled "lanes" were still distinguishable from surrounding seagrasses 14 months after trampling ended.

Propeller damage

Monroe County has approximately 12,141 hectares (30,000 acres) of significantly scarred seagrass beds, more than any other county in Florida. Most propeller damage is done by inexperienced or careless boaters. Propeller damage not only destroys the seagrasses in the pathway, but can also result in a change in the hydrology of the bed from the altered movement of water through the channel within the scar. Propeller scars may take 10 – 17 years to recover. If the scar is deep enough it will require filling to allow rhizomes to grow across the unvegetated gap.

Anchoring

Anchors, anchor chains, and mooring chains can physically destroy seagrasses by repeatedly battering leaves, rhizomes, and roots. Vessels permanently anchored often have a circular area surrounding the anchor that is scraped clean by the anchor chain as the vessel swings with wind and tide. Also, vessels anchored in one spot for an extended period can result in lethal shading of seagrasses. Anchoring in sandy areas can avoid damage to seagrasses.

Boat groundings

Boat groundings result in physical loss of seagrass beds and are offenses subject to both state and federal penalties. Violators are subject to costs of damage assessments, restoration of the habitat, and long-term monitoring of the restored habitat.

Dredging and filling for development has resulted in historic loss of seagrass and mangrove habitats

Alicia Farrer

Dredging and filling of coastal areas has caused the most destructive and widespread impacts to seagrass beds and mangroves in Florida. Florida ranks third among Gulf coastal states, after Texas and Louisiana, with the loss of approximately 9,712 hectares (24,000 acres) of submerged land that has been filled with dredge spoil.

A prime example of the loss of seagrasses by development in south Florida occurred during the construction of the Overseas Railroad by Henry Flagler in 1904 – 1912. This massive construction project linked mainland Florida and Key West by construction of a railroad bed that included 27 kilometers (17 miles) of bridges and over 32 km (20 mi) of causeways. Causeways were constructed by placing dredged and/or fill material in open shallow waters, including seagrass habitat. Completion of this project drastically altered the hydrodynamics and coastal morphology of the Florida Keys and was harmful to the environment. Although poorly documented, it is estimated that many hundreds of hectares of seagrasses and mangroves were destroyed by dredging and filling activities to construct the causeways.

Historical Preservation Society of the Upper Keys - keyshistory.org

An example of a dredge-and-fill canal residential development on Sugarloaf Shores, Lower Sugarloaf Key in the Florida Keys (ca. 1955). Canals were excavated by blasting and using a drag line in mangrove and shallow water seagrass habitats. Excavated material was used to create land by raising the elevation.

Causeways impede water flow, and in many areas they completely block tidal channels and creeks. This has resulted in restricted tidal exchange between Florida Bay and the Atlantic Ocean in some areas and has increased tidal flow and currents in other areas.

The Overseas Railroad was destroyed by a hurricane on September 2, 1935 (i.e., Labor Day Hurricane) and the Overseas Highway was built on top of the old railroad bed and bridges. Causeways were widened for the road by placing additional fill material in shallow water seagrass beds and mangrove habitats. In the 1980s, the modern highway was built and new, wider bridges were constructed. The deployment of large barges needed to build the new road required dredging of shallow bottoms to position and operate equipment.

The first subdivision in Key Largo was built in 1925; however, the main development of the Keys occurred from the 1940s – 1970s. The standard development practice consisted of creating waterfront developments by dredging canals in mangrove or shallow bottoms and using the fill to raise the elevation of the land for residential and commercial development.

Approximately 179 km (111 mi) of canals have been created in the Florida Keys, which has resulted in the loss of approximately half of the original mangrove habitat, and an unknown acreage of seagrass habitat. In addition to the habitat loss, many canals are very deep (i.e., more than 6 meters [20 ft]) and are devoid of benthic life due to sheer walls, lack of light, lack of oxygen on the bottom, and high nutrient levels. Sewage from septic tanks and cesspools used in early construction seeps into the canals because of the porous nature of the limestone substrate and the hydrologic gradient toward the canal.

Damage to seagrass beds from vessels can be restored

William F. Precht

Damage by boaters to seagrass resources in south Florida is significant. For example, there are as many as 600 reported vessel groundings annually in the Florida Keys National Marine Sanctuary and more than 90% of the groundings occur in seagrass habitats, resulting in blowholes and/or propeller scarring. The chronic nature of these repeated disturbances has reduced the ecological services and functions of the seagrass habitat at the landscape scale.

M. Stone

Shallow seagrass beds, such as this one in Florida Bay, are vulnerable to scarring from boat traffic. Scars are slow to heal and deep scars require filling.

Of the seven species of seagrass present in south Florida, turtle grass (*Thalassia testudinum*) is the most common, often forming monotypic beds that dominate the seascape. When vessel groundings in a turtle grass bed result in the removal of substrate (i.e., blowhole), natural recovery is nominal or nonexistent and the damage can persist for decades or longer because of the inability of turtle grass to grow downward to fill the damaged areas. Deepened areas also result in increased currents that can wash away loose sediments and prevent the reestablishment of new plants.

Replacement of lost sediments in trenches, blowholes, and deep propeller scars reduces the restoration time by allowing natural revegetation from adjacent areas into the restoration site. Fabric bags filled with sediments have been successfully used to fill depressions. The transplantation of seagrasses from local donor sites or from plant nurseries can further accelerate the recovery of damaged sites.

Scientists have discovered that shoal grass (*Halodule wrightii*) is a fast growing, early succession seagrass that can be planted as a temporary substitute for turtle grass. This method of restoration duplicates the natural succession of seagrass species and turtle grass becomes established in the planted area in time. Bird roosts can be placed to attract seabirds that provide a cost effective method for fertilizing seagrass restoration sites.

A seagrass restoration program is a viable management tool that can replace seagrasses lost from vessel damage. However, it is costly and success is not guaranteed. Groundings and propeller scarring are avoidable impacts. An effective boater education program can reduce damage from vessel impacts. Boaters need to learn to read and use navigation charts, read the water, and know the draft of their vessels.

NOAA

Placement of cloth tubes filled with sediments (Seagrass Recovery, Inc.) can hasten the recovery of deep propeller scars and blowholes by allowing seagrasses to grow across the damaged area.

Birds help facilitate seagrass restoration

Alicia Farrer

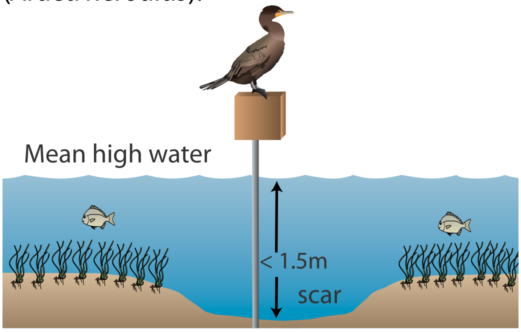
Boat groundings and propeller scarring cause significant damage to south Florida seagrass beds. When a boat runs aground on a seagrass bed, it damages plant material growing above and below the bottom sediments. Disturbance to the plant and the surrounding sediments makes it very difficult for seagrasses to recolonize the damaged area. Deeper scars need to be filled in before seagrasses can grow across the damaged area.

A limiting factor for seagrass growth on shallow carbonate banks in south Florida is the availability of phosphorus. Experimentally adding phosphorus fertilizer to sediments results in more rapid seagrass growth. In the 1990s, researchers noticed that seagrasses were particularly abundant and lush in areas around channel markers and other pilings where birds were roosting. That observation resulted in the development of a method to facilitate restoration of damaged seagrass areas. Placement of bird perches in areas of damaged seagrasses attracts birds that defecate in the water. Nutrients from bird feces increase the rate of growth of surrounding seagrasses and result in more rapid plant colonization into damaged areas.

Bird stakes are normally constructed of PVC pipe with a wooden block mounted on top to serve as a perch. Double-crested cormorants (*Phalacrocorax auritus*) are very abundant in south Florida, particularly during winter months, and are the most frequently observed species using the bird stake perches. Other species regularly observed on bird stakes include least terns (*Sterna antillarum*), royal terns (*Sterna maxima*), brown pelicans (*Pelicanus occidentalis*), magnificent frigate birds (*Fregata magnificens*), and great blue herons (*Ardea herodias*).

M.O. Hall - FWRI

Double-crested cormorants roosting on bird stakes placed at a grounding site in a seagrass bed.



Stakes with roosting blocks (i.e., perches) attached are placed in areas of damaged seagrasses, such as propeller scars and grounding sites. Roosting birds defecate into the water, adding nutrients that stimulate seagrass growth and recovery across the damaged area.

In most instances, transplanting seagrasses occurs simultaneously with installation of bird stakes. The decision whether to plant the damaged site is based on the degree of exposure of the site to wave action, the density of fast-growing seagrass species in the surrounding area, and the composition of the substrate. Generally, an injury in an area with a high density of shoal grass (*Halodule wrightii*), a fast growing species, will not require planting because the insertion of bird stakes alone is usually sufficient to encourage colonization.

The possibility for bird stakes interfering with vessel navigation is low because stakes are installed in shallow water areas that should be avoided by vessels. Bird stakes are removed from the site when recovery is determined well underway.

Seagrass restoration in Biscayne Bay provides lessons for other locations

Gary R. Milano

Biscayne Bay is one of the most valuable natural resources in south Florida. The Bay provides habitat for a productive and diverse community of subtropical marine plants and animals. It offers a variety of commercial and recreational opportunities to visitors and over 2 million residents of metropolitan Miami-Dade County. The Bay is a shallow estuary, measuring 56 kilometers (35 miles) from north to south and varying in width from approximately 1.6 – 13 km (1 – 8 mi). It covers an area of 570 km^2 (220 mi^2). The Bay is bordered on the west by the greater Miami area and on the east by a series of barrier islands and submerged vegetated banks.

Rapid urbanization and associated coastal development has severely altered natural habitats in Biscayne Bay. The northern third of the Bay (North Bay) is most severely impacted by development, and is subdivided by six causeways and a major seaport facility. Native coastal habitats have been virtually eliminated in North Biscayne Bay. Over 50% of the existing bottom in North Bay is barren, caused by the creation of deep dredge holes, spoil placement, and associated chronic elevated turbidity levels.

Damage to turtle grass rhizomes from a motor boat propeller. Turtle grass rhizomes only grow laterally. Thus, deep seagrass scars need to be filled quickly after damage in order to allow regrowth and stabilize the existing seagrass bed.

Map of Biscayne Bay showing the boundaries of Biscayne National Park and Biscayne Bay Aquatic Preserve.

Approximately 60% of Biscayne Bay is covered with seagrasses. The Central Bay is a transition zone between the heavily urbanized northern basins to the relatively pristine South Bay area. Biscayne National Park, established in this area of the Bay, was created to preserve and protect a rare combination of terrestrial, marine, and amphibious life for the enjoyment of present and future generations.

Large-scale seagrass restoration efforts

Port of Miami Seagrass Mitigation Project

The environmental regulatory authorization to expand the Miami Seaport Facility (1980) in North Bay required the planting of 61 hectares (151 acres) of Bay bottom with seagrasses to offset the loss of 33 ha (81 ac) of grass beds. The planting was to take place in two phases. Phase I included planting and monitoring one 10 ha (25 ac) plot and

Seagrass restoration requires containment of turbidity during the replacement of sediments within damaged seagrass areas.

thirteen 0.4 ha (1 ac) plots to test planting methods. Phase II was to include planting 86 ha (213 ac). The goal of the restoration was to achieve an overall survival rate of 70%; however, only 22% of test plots in Phase I achieved that survival rate. In 43% of the test plots, the degree of survival was rated a total loss. Overall, one year after planting the mean survival rate was 12%. Phase II was scaled back to a 8 ha (20 ac) site in North Bay and a 30 ha (73 ac) site in Central Bay. Survival after one year was 12% and 10% respectively. Because of the poor success with seagrass restoration, an alternative mitigation plan was implemented involving mangrove restoration, artificial reef creation, and shoreline stabilization.

Restoration of a dredged area in North Bay

In 1988, a study to evaluate alternative techniques for filling existing dredged areas in North Bay was planned for a 1 ha (2.6 ac) site. The dredged area was filled with dredge material from a Port of Miami expansion project and clean fill from a local rock mine. In 1994, a total of 12,957 planting units were installed (*Halodule*, *Syringodium*, *Thalassia*). After one year, survival of *Thalassia* units was 65%. The *Halodule* and *Syringodium* plots contained 60% coverage.

Biscayne National Park Damage Recovery Program

Shallow seagrass habitat in the Park is frequently impacted by vessel groundings. These incidents create specific types of injuries, such as propeller scars, blowholes, and berms. Seagrass restoration has been completed at 15 sites in the Park. In total, restoration actions at these sites included filling excavations with 187 cubic meters (244 cubic yards) of sediment fill, installing 339 bird stakes and 100 fertilizer packets, and transplanting 1,973 seagrass planting units. Monitoring for long-term success is conducted at all sites.

Lessons learned

- Water quality, including turbidity, and physical site conditions (e.g., current, substrate type, depth, wave energy), have been found to be important factors determining the success of seagrass restoration efforts.
- Seagrass planting is generally more successful when restoration is conducted at sites where a seagrass community previously existed, provided that conditions have improved to allow seagrass recruitment and survival.
- Specific restoration methodologies have been developed for various types of seagrass restoration. Restoration efforts are underway to restore damage caused by propeller scars and boat groundings, as well as the filling of previously dredged areas in Biscayne Bay.
- Seagrasses have been documented to naturally recruit into stabilized restored bay bottom.
- Herbivory has been observed to occur in newly transplanted restoration sites. Evaluations are underway to develop recommendations for the transplanting of restored sites to maximize success.
- Enhanced navigational signage, boating education programs, and motor boat exclusion zones are effective management tools to protect and conserve seagrass communities.

You can help protect seagrass beds

Alicia Farrer

Seagrass meadows are beautiful!

In addition to their ecological and economic value, seagrass habitats are also places of beauty and wonder. Seagrass meadows are home to a wide variety of marine life, from the tiniest crabs and shrimp to sting rays, sea turtles, and manatees. A close look at a seagrass meadow will reveal the complexity of the community that seeks shelter and food between the blades of grass.

A.V. Uhrin - NOAA

Healthy seagrass habitats support complex and diverse marine communities.

Remember this jingle to help you navigate in coastal waters of south Florida:

Brown, brown, run aground!
Avoid brown areas. This color indicates that hardbottom, coral reef formations, or seagrass beds are close to the surface.

White, white, you just might!
Use caution, sand bars and rubble areas may be much more shallow than they appear.

Green, green, nice and clean!
Green waters are generally safe for shallow draft boats. Larger, deeper draft vessels should use caution. When in doubt, check the navigation chart.

Blue, blue, cruise on through!
Blue waters are deep areas; clear sailing.

Be a seagrass-friendly boater

- Familiarize yourself with the waters and use up-to-date nautical charts.
- Wear polarized sunglasses to improve visibility below the water.
- Learn to use your electronic navigation equipment such as Global Positioning System (GPS).
- Learn where channel markers are located and use them to stay in deep water.
- Slow down to idle speed and raise the motor, when in doubt.
- Keep track of the tides. Use extra caution when boating at the time of low tide.
- Respect no motor zones and no entry zones.
- Do not anchor in seagrasses. Use a push pole to hold your position in seagrasses or use a mooring buoy if available. Otherwise, anchor in sandy areas at a sufficient distance from seagrasses so that the anchor and chain do not drag over seagrasses.
- If you inadvertently motor up on a seagrass flat, you will leave a sediment trail behind the boat. Stop immediately and tilt up the motor. Pole or push the boat to deeper water.
- If you run firmly aground, wait until the next high tide to float your boat off the seagrass bed. Do not try to power your way off the bed. Powering off is illegal and can subject you to severe fines and civil liability. Call for commercial assistance and notify the Coast Guard of your position on VHF Channel 16.

K Battle - BNP

Biscayne National Park has documented over 700 boat groundings since 1995. Boat groundings destroy fragile marine environments. Be a responsible boater and stay in marked channels.

Introduction citations

1. Florida Seagrass Outreach Partnership. 2007. Seagrass...it's alive! Available from: http://flseagrass.org/index.php (Cited 18 Feb 2011). *General information on the ecology and restoration of seagrasses.*
2. Florida Fish and Wildlife Conservation Commission. Fish and Wildlife Research Institute. Seagrass vs. Seaweeds. Available from: http://myfwc.com/research/habitat/seagrasses/information/seagrass-vs-seaweed/ (Accessed 17 Feb 2011). *Differences between seagrasses and seaweeds.*
3. Witherington D. 2006. Florida's Seagrasses. Loxahatchee River District, Poster Series, No. 1. Available from: http://www.loxahatcheeriver.org/pdf/seagrasses_poster_8.5x11.pdf (Accessed 17 Feb 2011). *Poster showing seven species of seagrasses found in Florida and their importance.*
4. National Oceanic and Atmospheric Administration. Office of Protected Species. Johnson's seagrass (*Halophila johnsonii*). Available from: http://www.nmfs.noaa.gov/pr/species/plants/johnsonsseagrass.htm (Accessed 18 Feb 2011). *Distribution and ecology of Johnson's seagrass.*
5. Heidelbaugh WS, Hall LM, Kenworthy WJ, Whitfield P, Virnstein RW, Morris LJ, Hanisak MD. 2000. Reciprocal transplanting of the threatened seagrass *Halophila johnsonii* (Johnson's seagrass) in the Indian River Lagoon, Florida. In: Bortone SA (ed.). Seagrasses: Monitoring, Ecology, Physiology, and Management. Boca Raton, FL: CRC Marine Science Series 16, CRC Press. p 1977-210. *Johnson's seagrass reproduces and spreads by vegetative growth.*
6. Fourqurean JW, Willsie A, Rose CD, Rutten LM. 2001. Spatial and temporal pattern in seagrass community composition and productivity in south Florida. Mar Biol. 138:341-354. *Description of distribution and seasonal changes in productivity of seagrasses in south Florida.*
7. Jaap WC, Hallock P. 1990. Coral Reefs. In: Myers RL, Ewel JJ (eds.). Ecosystems of Florida. Ecosystems of Florida. Orlando, FL: University of Central Florida Press. p 574-616. Univ. Orlando, FL: Central Florida Press. p. 574-616. *Seagrass distribution, functions, and values.*
8. Rose CD, Sharp WC, Kenworthy WJ, Hunt JH, Lyons WG, Prager EJ, Valentine JF, Hall MO, Whitfield P, Fourqurean JW. 1999. Sea urchins overgrazing a large seagrass bed in outer Florida Bay. Mar Ecol Prog Ser. 190:211-222. *Dense population of* Lytechinus variegatus *ate a large area of* Syringodium filiforme *north of Marathon, FL.*
9. Heck Jr. KL, Carruthers TJB, Duarte CM, Hughes AR, Kendrick G, Orth RJ, Williams SW. 2008. Trophic transfers from seagrass meadows subsidize diverse marine and terrestrial consumers. Ecosystems 11:1198-1210. *Export of particulate organic matter and living plant an animal biomass from seagrass beds provides energy source for nearby communities.*
10. Valentine JF, Duffy JE. 2006. The central role of grazing in seagrass ecosystems. In: Larkum AWD, Orth RJ, Duarte CM (eds.). Seagrasses: Geology, Ecology, and Conservation. The Netherlands: Springer. p. 463-501. *Seagrasses are visited for grazing by animals found in other habitats.*
11. McKenzie LJ, Yoshida RL, Coles RG. 2006-2010. What is Seagrass? Available from: http://www.seagrasswatch.org/seagrass.html (Cited 18 Feb 2011). *Interactions and energy transfer between seagrass, coral, and mangrove habitats are described.*
12. Gillanders BW. 2006. Seagrass, fish, and fisheries. In: Larkum AWD, Orth RJ, Duarte CM (eds.). Seagrasses: Geology, Ecology, and Conservation. The Netherlands: Springer. p. 63-70. *Role of seagrasses in fisheries productivity.*
13. Fourqurean JW, Durako MJ, Hall MO, Hefty LN. 2002. Seagrass distribution in south Florida: A multi-agency coordinated monitoring program. In: Porter JW, Porter KW (eds.). The Everglades, Florida Bay and Coral Reefs of the Florida Keys: An Ecosystem Sourcebook. Boca Raton, FL: CRC Press. p. 497-522. *Assessment of species composition and density of seagrass species in the largest documented semicontinuous seagrass meadow on Earth.*
14. Dineen J. 2001. *Ruppia maritima* (Widgeon Grass). Smithsonian Marine Station at Fort Pierce. Available from: http://www.sms.si.edu/irlspec/Ruppia_mariti.htm (Updated 25 Jul 2001; cited 17 Feb 2011). *Taxonomy, life history, and ecology of widgeon grass. This species can tolerate a wide range of salinities.*
15. South Florida Water Management District. Water Management and Water Supply Departments. 2006. Draft Technical Document to Support Development of Minimum Flows and Levels for Florida Bay. Available from: http://www.sfwmd.gov/portal/page/portal/xrepository/sfwmd_repository_pdf/flbaydoc.pdf (Cited 18 Feb 2011). *Data analysis to determine salinity regime in coastal areas of Florida Bay to support seagrass (*Ruppia maritima*) growth.*
16. Phillips RC, Meñez EG. 1988. Seagrasses. Smithsonian Contributions to the Marine Sciences, Number 34. Washington, DC: Smithsonian Institution Press, 104 p. *General information on the ecology, physiology, biology, and evolution of seagrasses.*
17. Bester, C. Seagrass Zonation. Florida Museum of Natural History, South Florida Aquatic Environments. Available from: http://www.flmnh.ufl.edu/fish/southFlorida/seagrass/zonation.html (Cited 17 Feb 2011). *Zonation pattern of Florida's seagrasses with depth.*
18. Diersing, N. 2009. Seagrass Meadows and Nutrients. Florida Keys National Marine Sanctuary. Available from: http://floridakeys.noaa.gov/pdfs/seagrass_nut.pdf (Cited 18 Feb 2011). *Relationship of seagrass with nitrogen and phosphorus limitation.*
19. Fourqurean JW, Zieman JC. 1992. Phosphorus limitation of primary production in Florida Bay: Evidence from C:N:P ratios of the dominant seagrass *Thalassia testudinum*. Limnol Oceanogr. 37:162-171. *Seagrass growth in eastern Florida Bay is limited by the availability of phosphorus.*
20. Fourqurean FW, Rutten LM, Philippi T. Florida Keys Carrying Capacity Study: Assessment of Nearshore Benthic Communities of the Florida Keys. Florida International University. Available from: http://serc.fiu.edu/seagrass/NearshoreWeb/NearshoreReport.htm (Cited 18 Feb 2011). *Little temporal variation of nearshore benthic communities in the Florida Keys through the past 40 years was observed, even in the face of a tremendous amount of land development.*
21. Fourqurean JW, Rutten LM. 2003. Competing goals of spatial and temporal resolution: Monitoring seagrass communities on a regional scale. In: Bush DE, Trexler JC (eds.). Monitoring Ecosystems: Interdisciplinary Approaches for Evaluating. Washington, DC: Island Press. p. 257-288. *Model showing changes in species composition of primary producers with increasing nutrient concentration.*
22. Fourqurean JW. 2008. Seagrass Monitoring in the Florida Keys National Marine Sanctuary. FY 08 Annual Report- Executive Summary. Available from: http://serc.fiu.edu/seagrass/ExecutiveSummaryFY08.pdf (Cited 18 Feb 2011). *Early signs of eutrophication are observed in some seagrasses at permanent monitoring stations in the Florida Keys.*
23. Fourqurean JW, Robblee MB. 1999. Florida Bay: A history of recent ecological changes. Estuaries 22: 345-357. *Manipulation of water delivery in the south Florida ecosystem changed the character of Florida Bay's*

Seagrass Habitats

salinity regime. Changes in water delivery coupled with a period of drought resulted in die-off of turtle grass began in 1987.

24. Koch MS, Schopmeyer SA, Nielsen OI, Kyhn-Hansen C, Madden CJ. 2007. Conceptual model of seagrass die-off in Florida Bay: Links to biogeochemical processes. J Exp Mar Biol Ecol. 350:73-88. *High temperature and salinity resulted in a cascade effect resulting in seagrass die-off.*
25. Durako MJ, Kuss KM. 1994 Effects of *Labyrinthula* infection on the photosynthetic capacity of *Thalassia testudinum*. Bull Mar Sci. 54(3):727-732. *Presence of lesions impair photosynthesis and may reduce oxygen available for transport to underground tissues, possibly making turtle grass more susceptible to hypoxia and sulfide toxicity.*
26. Blakesley BA, Landsberg JH, Hall MO. 1998. Effects of Hurricane Georges on seagrass disease in Florida Bay: Were there any? Seahorse Sentinel 1(2): Winter 1998. Available from: http://www.floridabay.org/pub/sentinel/vol1-2.shtml (Cited 21 Feb 2011). *Relationship between salinity and seagrass disease in Florida Bay.*
27. Florida Department of Environmental Protection. 2003. Conserving Florida's Seagrass Resources: Developing a Coordinated Statewide Management Program. Florida Fish and Wildlife Conservation Commission, Florida Marine Research Institute, St. Petersburg, FL. 39 p. *Ecological and economic value of Florida's seagrass resources justify development of a statewide management program.*
28. Duke T, Kruczynski WL. 1992. Status and Trends of Emergent and Submerged Vegetative Habitats, Gulf of Mexico, U.S.A. U.S. Environmental Protection Agency 800-R-92-003, 161 p. *Over the past 50 years, 20 to 100% of seagrass acreage has been lost in estuaries of the northern Gulf of Mexico.*
29. National Oceanic and Atmospheric Administration, National Ocean Service. 2008. Lost Lobster Traps have Big Impact in Florida Keys. Available from: http://oceanservice.noaa.gov/news/weeklynews/dec08/lobstertraps.html (Updated 19 Dec 2008; cited 21 Feb 2011). *Spiny lobster traps have a large impact on seagrasses in the Florida Keys.*
30. Sargent FJ, Leary TJ, Kruer CR. 1995. Scarring of Florida's seagrasses: assessment and management options. Tech. Rept. TR-1, Florida Marine Research Institute, St. Petersburg, FL. 37 p. *Quantitative assessment of propeller scarring of seagrasses in Florida.*
31. Uhrin AV, and Fonseca MS. 2005. Effects of Caribbean spiny lobster traps on seagrass beds of the Florida Keys National Marine Sanctuary: Damage assessment and evaluation of recovery. Amer. Fish. Soc. Symp. 41: 579-588. *Lobster traps must be recovered within a 6-week period, beyond which injury to seagrass beds is predicted.* Syringodium *recovers slowest.*
32. Bell SS, Brooks RA, Robbins BD, Fonseca MS, Hall MO. 2001. Faunal response to fragmentation in seagrass habitats- implications for seagrass conservations. Conserv Biol. 100:115-123. *Fragmented seagrass beds do not provide the same quality of habitat as continuous acreage.*
33. Beck MW, Kruczynski WL, Sheridan PF. 2007. Conclusions. In: Handley LD, Altsman D, DeMay R (eds.). Seagrass Status and Trends in the Northern Gulf of Mexico: 1940-2002. U.S.G.S. Scientific Investigation Report 2006-5287 and U.S. EPA 855-R-04-003. p. 255-263. *Implementation of active alternatives instead of crisis management are proposed for the conservation of seagrass resources.*

Further reading

Armitage AR, Frankovich TA, Fourqurean JW. 2006. Variable responses within epiphytic and benthic microalgal communities to nutrient enrichment. Hydrobiologia 569: 423-435. *Responses to fertilization are variable in epiphytes and benthic microalgae.*

Armitage AR, Frankovich TA, Heck Jr KL, Fourqurean JW. 2005. Experimental nutrient enrichment causes complex changes in seagrass, microalgae, and macroalgae community structure in Florida Bay. Estuaries 28:422-434. *Responses to experimental fertilization of seagrass, microalgae, and macroalgae in Florida Bay are complex and variable.*

Bortone SA (ed.). 1999. Seagrasses: Monitoring, Ecology, Physiology, and Management. Boca Raton, FL: CRC Press. 336 p. *Comprehensive summary of seagrass ecology and management.*

Costanza R, d'Arge R, de Groot R, Farberparallel S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, Raskin RG, Sutton P, van den Belt M. 1997. The value of the world's ecosystem services and natural capital. Nature 387: 253 - 260. *Estimation of the current economic value of 17 ecosystem services for 16 biomes.*

Dawes CJ, Phillips RC, Morrison G. 2004. Seagrass Communities of the Gulf Coast of Florida: Status and Ecology. Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute and Tampa Bay Estuarine Program, St. Petersburg, FL. 74 p. *Comprehensive summary of distribution, status and trends, ecological roles, threats, and taxonomy of seagrasses on Florida's Gulf coast.*

Dennison WC, Orth RJ, Moore KA, Stevenson JC, Carter V, Kollar S, Bergstrom PW, Batiuk RA. 1993. Assessing water quality with submersed aquatic vegetation. BioScience 43:86-94. *Seagrasses are long-term integrators of water quality conditions.*

Duarte C M, Chiscano CL. 1999. Seagrass biomass and production: a reassessment. Aquat Bot. 65:159-174. *Biomass and production of seagrass populations were reassessed based on the compilation of a large data set comprising estimates for 30 species.*

Duarte CM, Marbà N, Gacia E, Fourqurean JW, Beggins J, Barrón C, Apostolaki ET. 2010. Seagrass community metabolism: assessing the carbon sink capacity of seagrass meadows. Global Biogeochem Cycles 24: 8 p. *The global loss of 29% of the seagrass area represents a major loss of natural carbon sinks in the biosphere.*

Eiseman NJ, McMillan C. 1980. A new species of seagrass, *Halophila johnsonii*, from the Atlantic coast of Florida. Aquat Bot. 9:15-19. *Description of new species of seagrass ranging from Sebastian Inlet to Biscayne Bay.*

Engeman RM, Duquensnel JA, Cowan EM, Smith HT, Shwiff, SA, Karlin M. 2008. Assessing boat damage to seagrass bed habitat in a Florida part from a bioeconomics perspective. J Coastal Res. 24:527-532. *Increased signage and law enforecement staff are the most immediate and practical measures to prevent seagrass damage from boats.*

Ferdie M, Fourqurean JW. 2004. Responses of seagrass communities to fertilization along a gradient of relative availability of nitrogen and phosphorus in a carbonate environment. Limnol Oceanogr. 49:2082-2094. *Offshore beds were strongly limited by nitrogen and nearshore beds were affected by nitrogen and phosphorus. Adding phosphorus may have importat long-term effects on benthic communities.*

Fonseca MS, Kenworthy WJ, Thayer GW. 1998. Guidelines for the Conservation and Restoration of Seagrasses in the United States and Adjacent Waters. National Oceanic and Atmospheric Administration, Coastal Ocean Program Decision Analysis Series No. 12, NOAA Coastal Ocean Office, Siver Spring, MD. *Comprehensive summary of restoration methods for seagrasses.*

Fourqurean JW, Boyer JN, Durako MJ, Hefty LN, Peterson BJ. 2003. Forcasting responses of seagrass distribution to changing water quality using monitoring data. Ecol Appl. 13:474-489. *An increase in seasonal delivery of* *freshwater to Florida Bay should cause an increase in widgeon grass and shoal grass at the expense of turtle grass in northeast Florida Bay.*

Fourqurean J W, Escorcia SP, Anderson WT, Zieman JC. 2005. Spatial and seasonal variability in elemental content,13C, and 15N of Thalassia testudinum from south Florida and its implications for ecosystem studies. Estuaries 28:447-461. *Seasonal and natural variability in isotopic values is greater than the signal often used to imply changes in structure and function of ecosystems.*

Fourqurean JW, Muth MF, Boyer JN. 2010. Epiphyte loads on seagrasses and microphytobenthos abundance are not reliable indicators of nutrient availability in coastal ecosystems. Mar Pollut Bull. 60:971-983. *Epiphyte load on turtle grass was not correlated with nutrients in sediments or water column in an oligotrophic grass bed.*

Fourqurean JW, Powell GVN, Kenworthy WJ, Zieman JC. 1995. The effects of long-term manipulation of nutrient supply on competition between the seagrasses Thalassia testudinum and Halodule wrightii in Florida Bay. Oikos 72:349-358. *Sea bird fertilization changed seagrass community and effects of fertilization persisted at least eight years after cessation of nutrient addition.*

Fourqurean JW, Rutten LM. 2004. The impact of Hurricane Georges on soft-bottom, back reef communities: Site- and species-specific effects in south Florida seagrass beds. Bull Mar Sci. 75:239-257. *Hurricanes may increase macrophyte diversity by creating distrubed patches within the landscape, but moderate storms may reduce diversity by removing early successional species from mixed-species beds.*

Fourqurean J W, Zieman JC. 2002. Seagrass nutrient content reveals regional patterns of relative availability of nitrogen and phosphorus in the Florida Keys, USA. Biogeochemistry 61:229-245. *Nutrient concentration in seagrass leaves varies with nutrient limitation.*

Green EP, Short FT (eds.). 2003. World Atlas of Seagrasses. Berkeley, CA: University of California Press. 298 p. *Regional and world maps of seagrass distribution and summary of seagrass ecology and values.*

Hall MO, Durako MJ, Fourqurean JW, Zieman JC. 1999. Decadal changes in seagrass distribution and abundance in Florida Bay. Estuaries 22:445-459. *Long-term look at seagrass species distribution and abundance in Florida Bay during the 1980s and 1990s, spanning the period of heavy die-off.*

Herbert DA, Fourqurean JW. 2008. Ecosystem structure and function still altered two decades after short-term fertilization of a seagrass meadow. Ecosystems 11:688-700. *A seagrass meadow fertilized by seabird defecation experienced a shift in species from turtle grass to shoal grass within six years and remained altered with 23 years of continuous fertilization. When fertilization was discontinued after three years, turtle grass re-established itself as the dominant species, but shoal grass has maintained a presence due to functional changes in the phosphorus cycle.*

Herbert DA, Fourqurean JW. 2009. Phosphorus availability and salinity control productivity and demography of the seagrass *Thalassia testudinum* in Florida Bay. Estuar Coasts 32:188-201. *Factors limiting distribution and abundance of turtle grass in Florida Bay.*

Hunt J, Nuttle W. 2007. Florida Bay Science Program: A Synthesis of Research on Florida Bay. Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute Technical Reptort TR-11, 148 p. *Summary of ecosystem history, physical processes, nutrient dynamics, plankton blooms, seagrass ecology, and higher trophic level species in Florida Bay.*

Kennedy H, Beggins J, Duarte CM, Fourqurean JW, Holmer M, Marbà N, Middelburg JJ. 2010. Seagrass sediments as a global carbon sink: isotopic constraints. Global Biogeochem Cycles 24: 8 p. *Seagrass meadows are natural hot spots for carbon sequestration.*

Lapointe BE, Barile PJ. 2004. Comment on J.C. Zieman, J.W. Fourqurean and T.A. Frankovich.1999. Seagrass dieoff in Florida Bay (USA): Long-term trends in abundance and growth of *Thalassia testudinum*. Estuaries 27: 157-164. *Critique of Florida Bay die-off model.*

Littler DS, Littler MM, Hanisak MD. 2008. Submersed plants of the Indian River Lagoon. Washington, DC. OffShore Graphics Inc. 298 p. *Handbook of identification of submerged aquatic vegetation.*

Macia S, Lirman D. 1999. Destruction of Florida Bay seagrasses by a grazing front of sea urchins. Bull Mar Sci. 65:593-601. *A large (several kilometers long) aggregation of the sea urchin* Lytechinus variegatus*, first detected in August 1997, caused significant damage grazing on dense beds of the seagrass* S. filiforme *in the western portion of Florida Bay.*

Madden CJ, Rudnick DT, McDonald AA, Cunniff KM, Fourqurean JW. 2009. Ecological indicators for assessing and communicating seagrass status and trends in Florida Bay. Ecol Indic. 95:S68-S82. *Ecological indicators are proposed that will provide a method to assess progress toward restoration of a diverse, multi-species seagrass community after hydrological restoration.*

Montague CL, Ley LA. 1993. A possible effect of salinity fluctuation on abundance of benthic vegetation and associated fauna in northeastern Florida Bay. Estuaries 16:703-717. *Changes in salinity affect benthic community structure in Florida Bay.*

Orth RJ, Carruthers TJB, Dennison WC, Duarte CM, Fourqurean JW, Heck Jr. KL, Hughes AR, Kendrick GA, Kenworthy WJ, Olyarnik S et al. 2006. A global crisis for seagrass ecosystems. BioScience. 56:987-996. *Seagrasses are challenged by rapid environmental changes as a result of coastal human population growth.*

Powell GVN, Kenworthy WJ, Fourqurean JW. 1989. Experimental evidence for nutrient limitation of seagrass growth in a tropical estuary with restricted circulation. Bull Mar Sci. 44:324-340. *Fertilization by sea birds causes growth in turtle grass and shoal grass. Phosphorus availability may limit seagrass growth in unenriched conditions, but nitrogen becomes limiting with the addition of bird excrement.*

Powell GVN, Fourqurean JW, Kenworthy WJ, Zieman JC. 1991. Bird colonies cause seagrass enrichment in a subtropical estuary: observational and experimental evidence. Estuar Coast Shelf Sci. 32:567-579. *Fertilization by sea birds can change species composition of seagrass beds.*

Robblee MB, Barger TR, Carlson PR, Durako MJ, Fourqurean JW, Muehlstein LK, Porter D, Yargro LA, Ziemen RT, Zieman JC. 1991. Mass mortality of the tropical seagrass *Thalassia testudinum* in Florida Bay (USA). Mar Ecol Prog Ser. 71:297-299. *History of events leading up to seagrass die-off and impact to community structure in Florida Bay.*

Schwarzschild AC, Kenworthy WJ, Zieman JC. 2008. Leaf growth of the seagrass Syringodium filiforme in outer Florida Bay, Florida. Bull Mar Sci. 83:571-585. *New technique based on the growth of emergent leaves is a preferred method for measuring growth of manatee grass.*

Thayer GW, Powell AB, Hoss DE. 1999. Composition of larval, juvenile, and small adult fishes relative to changes in environmental conditions in Florida Bay. Estuaries 22:518-533. *Documentation of a shift toward a planktonic-feeding community in Florida Bay following seagrass die-off and increase in phytoplankton biomass.*

Thomas LP, Moore DR, Work RC. 1961. Effects of hurricane Donna on the turtle grass beds of Biscayne Bay, Florida. Bull Mar Sci Gulf Caribb. 11:191-197. *The dry* *and wet weight of* Thalassia testudinum *washed ashore at Biscayne Bay during Hurricane Donna of 1960 is estimated.*

Valentine JF, Heck Jr KL. 1999. Seagrass hervivory: evidence for the continual grazing of marine grasses. Mar Ecol Prog Ser. 176:291-302. *Evidence suggests that the currently accepted view that herbivory plays a minor role in the energetics of seagrass habitats needs to be reexamined by measuring seagrass responses to grazer induced tissue losses in controlled field manipulations.*

Whittaker RH. 1975. Communities and Ecosystems, Ed. 2. New York: Macmillian Publ. Co. 385p. *General ecology textbook.*

Zieman JC. 1982. The Ecology of the Seagrasses of South Florida: A Community Profile. U.S. Fish Wildl. Serv. Off. Biol. Serv. Tech. Rept. FWS/OWS 82-25, Washington, D.C. *Excellent introduction to the ecology of seagrass communities in south Florida.*

Zieman JC, Fourqurean JW, Frankovich TA. 1999. Seagrass die-off in Florida Bay (USA): Long-term trends in abundance and growth of *Thalassia testudinum*. Estuaries 22:460-470. *Hypersalinity was one of the contributing factors to seagrass die-off in Florida Bay.*

Zieman JC, Fourqurean JW, Frankovich TA. 2004. Reply to BE Lapointe and PJ Barile. 2004. Comment on Zieman JC, Fourqurean JW, Frankovich TA. 1999. Seagrass die-off in Florida Bay (USA): Long-term trends in abundance and growth of *Thalassia testudinum*. Estuaries 26: 1548-1555. *Defense of previously published work on seagrass die-off in Florida Bay.*

Zieman JC, Thayer GW, Robblee MB, Zieman RT. 1979. Production and export of seagrasses from a tropical bay. In: Livingston RJ. (ed.). Ecological Processes in Coastal and Marine Systems. New York: Plenum Press. p. 21-33. *Importance of primary production to seagrass beds and adjacent marine ecosystems.*

Zieman JC, Wetzel RG. 1980. Productivity in seagrasses: methods and rates. In: Phillips RC, McRoy CP (eds.). Handbook of Seagrass Biology, an Ecosystem Prospective. New York: Garland STPM Press. p. 87-116. *A comparison of methods to measure seagrass primary production.*

Website references

Brewster-Wingard L, Ishman SE, Holmes CW, Willard DA, Edwards LE. Environmental change in the Florida Bay ecosystem: Patterns over the last 150 years. United States Geological Survey, South Florida Information System. Available from: http://sofia.usgs.gov/projects/eh_fbswc/ehfbswcab2.html (Updated 11 Oct 2002; accessed 22 Feb 2011). *Analyses of the faunal and floral record in short sediment cores from three sites in the central portion of Florida Bay document changes in salinity.*

Diersing N. 2009. Phytoplankton Blooms in Florida Bay. Florida Keys National Marine Sanctaury. Available from: http://floridakeys.noaa.gov/pdfs/wqbloom.pdf (Accessed 22 Feb 2011). *Algal blooms in Florida Bay cause widespread concerns.*

Hill K. 2001. A comparison of algal morphology and seagrass morphology. Smithsonian Marine Station at Fort Pierce. Available from: http://www.sms.si.edu/irlspec/ComparAlgae_Seagr.htm (Updated 25 Jul 2001; accessed 27 Jul 2011). *Differences between algae and seagrasses.*

Historical Preservation Society of the Upper Keys. Keys Historeum. Available from: http://keyshistory.org/ (Accessed 7 Sept 2011). *Detailed history of the Florida Keys.*

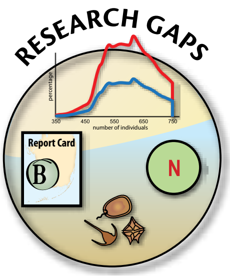
Milano GR, Deis, DR. 2006. Biscayne Bay seagrasses and recent restoration efforts. In: Treat SF, Lewis III RR (eds.) Seagrass Restoration: Success, Failure, and the Costs of Both. Selected Papers of Seagrass Restoration Workshop, Mote Marine Laboratory, March 2003. Available from: http://www.seagrassrestorationnow.com/docs/Treat%20and%20Lewis%202006%20Seagrass%20Restoration-6.pdf (Accessed 22 Feb 2011). *Summarizes seagrass restoration efforts in Biscayne Bay from 1980 to present.*

United States Geological Survey, South Florida Ecosystem History Project. Florida Bay. Available from: http://sofia.usgs.gov/flaecohist/floridabay.html (Updated 1 Sept 2006; accessed 22 Feb 2011). *An examination of the patterns of benthic faunal distribution seen in core samples from Florida Bay revealed that changes in salinity and substrate are part of the natural system.*

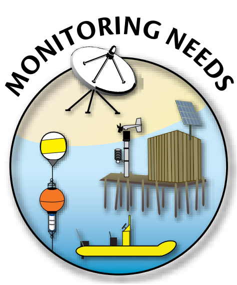
6. MANGROVE HABITATS

Mangrove Habitats
Chapter Recommendations

- Provide land use planners with reliable information on how mangrove forests will respond to **sea-level rise** and other effects of climate change.
- Develop comprehensive strategies to mitigate effects of **climate change** on mangrove communities.
- Support mangrove restoration efforts to replace **historically lost mangrove communities**.
- Support effective education programs to inform citizens on the **economic benefits** of conserving the remaining mangrove forests in south Florida.
- Sponsor mangrove cleanups and planting events to raise **public awareness** and appreciation of mangrove resources.



- Quantify importance of **mangrove shorelines** to estuarine and reef fish assemblages.
- Quantify functions of mangrove habitats located high in the **intertidal zone**.
- Determine role of **dissolved organic matter** exported from mangroves through surface runoff and groundwater.
- Continue to explore better and more cost effective **methods to restore** mangrove communities.
- Quantitatively evaluate **ecosystem functions** of restored mangrove communities.
- Quantify **processing and flux of nutrients** in mangrove forests.



- Evaluate the ability of **remote sensing** in quantifying mangrove acreage.
- Monitor **long-term recovery** of mangrove forests from hurricanes or other natural perturbations.
- Systematically monitor remaining mangrove coverage, particularly adjacent to **developed areas**.

Chapter title page: Red mangrove forest, Shark River, Everglades National Park. R.R. Twilley, LSU

Introduction

What is a mangrove?

Mangrove forests are among the most productive ecosystems in the world. Mangroves are woody plants that grow in tropical and subtropical latitudes along the land-sea interface, and in bays, estuaries, lagoons, backwaters, and tidal rivers. These plants and their associated organisms (e.g., microbes, fungi, other plants and animals) constitute the mangrove forest community or "mangal".[1,2,3] Plants within the mangal have characteristics that allow them to live in salty environments. Mangrove tree species have morphological adaptations, such as aerial roots and pneumatophores, reproductive strategies, such as the formation of propagules, and physiological mechanisms, such the ability to excrete salt.[1,4,5] Three native species of true mangrove trees occur in south Florida: red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*). The buttonwood tree (*Conocarpus erectus*) is a mangrove associate and does not exhibit root modifications or propagule formation. It is a tree species that exists along the upland fringe of many mangrove forests.[6]

Factors controlling mangrove distribution

Mangroves trees are tropical plants that usually do not occur in areas where the annual average temperature is below 19°C (66°F). They can not tolerate temperatures below freezing for more than a few hours.[1] Approximately 90% of the mangrove forests in Florida occur in the four southernmost counties: Lee, Collier, Miami-Dade, and Monroe. The black mangrove is the most cold-tolerant of the three mangrove species. Its range extends to the northern coast of the Gulf of Mexico, where it exists as a shrub from root regeneration after freezes.[1]

ENP

Red mangrove trees produce prop roots that supply air to the underlying roots and provide support and stability to the tree.

W.L. Kruczynski - EPA

Dwarf black mangroves with pneumatophores. Pneumatophores are adaptations that allow mangroves to grow in soils with little or no oxygen. They grow from the underground root system and deliver oxygen to roots.

Mangroves do not require saltwater to live, but can tolerate saline environments better than many other vascular plants. They also can grow in freshwater, but are outcompeted by other plants in most freshwater environments. They grow best in intertidal areas and in places with low wave energy. Tidal fluctuations serve to distribute mangrove reproductive propagules, transport nutrients, and flush potentially toxic hydrogen sulfide and excess salts from soils. Mangrove forests reach their greatest height and biomass in areas where they can intercept nutrients from terrestrial runoff, such as at the mouths of a myriad of tidal creeks and rivers that exist at the margin of the Everglades in the Ten Thousand Islands.[7]

Mangrove Habitats

Mangroves grow in five types of communities that are controlled by topographic and hydrological functions. Fringing mangrove forests occur along edges of low energy shorelines, canals, and rivers where the elevation is higher than the mean high tide. Overwash mangrove forests are found on relatively small, low islands that are completely inundated by daily tides. Riverine mangrove forests grow along flowing tidal rivers and creeks and are flushed daily by tides. Basin mangrove forests occur in inland depressions where water is stagnant or slow flowing and are flooded irregularly by the highest tides. Scrub (dwarf) mangrove forests occur in areas where soil, nutrients, freshwater, and tidal inundation are limited.[8,9]

The value of mangroves

Mangrove forests provide many important ecological services. Their extensive root system stabilizes sediments and protects shorelines. They intercept nutrient runoff from upland sources and thus protect and improve water quality. Mangrove forests can be as productive as a cultivated wheat field, and they export a large portion of that productivity as leaf and litter fall to nearby estuarine waters.[4,7,10] There, it is processed into mangrove detritus and dissolved organic matter and forms the base of a complex food web.[11] Mangroves provide critical nursery habitat for commercial and recreationally important species, such as spiny lobster, shrimp, tarpon, snook, gray snapper, and goliath grouper. Other species are only found in mangrove habitats, such as the mangrove cuckoo and mangrove snake. Many wading birds nest and roost in mangroves, including the wood stork, heron, egret, ibis, roseate spoonbill, cormorant, and pelican. These habitats are also an important stopover for migrant passerine birds, such as warblers, buntings, and others. Several species of special concern, such as the American crocodile, rely on mangrove habitats for food and shelter.

M. Stone

Roseate spoonbills are one of the many bird species that use mangrove forests as nesting and roosting areas.

P.J. Fletcher - FSG

Mangrove forests provide educational opportunities.

An often overlooked value of mangrove forests is their aesthetic appeal. Mangrove wildernesses provide recreational opportunities to experience nature, fishing, hiking, camping, bird watching, and relaxing. In many heavily developed areas, mangrove thickets in preserves and conservation easements are the only relatively pristine natural habitat remaining. The mangrove forest along the edge of the Everglades, particularly in the Ten Thousand Islands, is one of the largest and most significant wilderness areas in south Florida. Many view the existence of these remaining wilderness areas as a near religious experience, and the mere knowledge of their existence can bring solace in an otherwise hectic lifestyle.

Threats to mangroves

Mangrove forests are susceptible to damage from natural calamities, such as hurricanes and lightning strikes,[12] and human-induced destruction from dredging, filling, impounding, cutting and trimming, oil spills, and accumulation of trash.[1,4,13] Roughly 50% of the global mangrove area has been lost since 1900, and 35% has been lost in the past two decades.[14,15] Urban, industrial, and agricultural development has resulted in the largest losses or degradation of mangrove habitats throughout Florida. For example, 87% of the mangrove shoreline in Lake Worth has been destroyed. Approximately 86% of the original mangrove wetlands in the Indian River Lagoon have been impounded or otherwise lost to fisheries productivity.[16] In the Upper Florida Keys, approximately 60% of shallow water mangroves were lost between 1965 – 1985; 40% of that loss was due to dredging and filling.[17] If these trends continue, mangrove habitats in south Florida may be depleted beyond their ability to naturally recover.

A. M. Molina Fletcher

Red mangrove showing prop roots secured among rocky intertidal area, Broward County, Florida.

A. M. Molina Fletcher

White mangrove growing in Broward County, Florida.

Climate change is resulting in a rise in sea level due to expanding ocean water and the melting of glaciers, ice caps, and ice sheets in Greenland and the Antarctic. The Intergovernmental Panel on Climate Change estimates that the global average sea level will rise between 0.20 – 0.56 meters (8 – 22 inches) within the next century.[18] The range reflects uncertainty about global temperature projections and how rapidly ice sheets will melt or slide into the ocean in response to the warmer temperatures. Regardless of the exact amount of sea-level rise, the Panel has concluded that the impacts of sea-level rise are "virtually certain to be overwhelmingly negative," particularly to wetlands and other low-lying lands.[18] As the sea rises, the outer boundary of mangrove forests will erode, and new wetlands will form inland as previously dry areas are flooded by the higher water levels. However, the acreage of newly created wetlands may be much smaller than the lost area of wetlands, especially in developed areas that are protected with bulkheads, dikes, and other structures that keep new wetlands from forming inland. The Panel suggests that by 2080, sea-level rise could convert as much as 33% of the coastal wetlands in the world to open water.[18] Wetlands with small tidal ranges are the most vulnerable. A U. S. Environmental Protection Agency

Report to Congress has estimated that 1 m (3 feet) rise in sea level could eliminate 25 – 80% of coastal wetlands in the United States, with more than half the loss taking place in Louisiana.[19]

Much of the remaining mangrove forests in south Florida exist as isolated fragments, with the exception of the large contiguous forests along the southwest coast. In many cases, mangroves are restricted to a narrow fringe along the coast, creating a thin border between development and tidal embayments or along rivers. Given their limited range and inability to expand inland, these fragmented habitats are at great risk from sea-level rise. Changes in freshwater inputs could also threaten the long-term survival of these systems.

Mangrove restoration

Mangroves can be successfully planted in areas that are suitable for growth, even if they have been previously destroyed in that location. Transplants do best when planted in natural substrates where wave energy is not excessive. At appropriate sites with normal or near-normal tidal hydrology and with establishment of mangroves through natural recruitment or planting, restored mangrove systems can become indistinguishable from nearby natural mangrove systems within a relatively short time. Dense thickets of mangrove shrubs can develop within five years of plant establishment. In south Florida and other subtropical or tropical regions, forests with trees taller than 5 m (16 ft) with well-established prop root and pneumatophore networks, and with closed canopies, can develop within 15 years.[20]

Future trends in the status of mangrove habitats in south Florida are difficult to predict. The pressures for increasing development are intense and are fueled by increasing population growth. People desire to live near open water, which threatens remaining mangrove shorelines that currently exist in areas not under public ownership or management. It remains to be seen whether local, state, or federal governments will be able to continue to protect remaining mangrove ecosystems through strong legislative and regulatory efforts.[1,21,22,23]

A. M. Molina Fletcher

Red mangrove prop roots in a low energy environment.

Mangroves have adapted to survive in tropical coastal environments

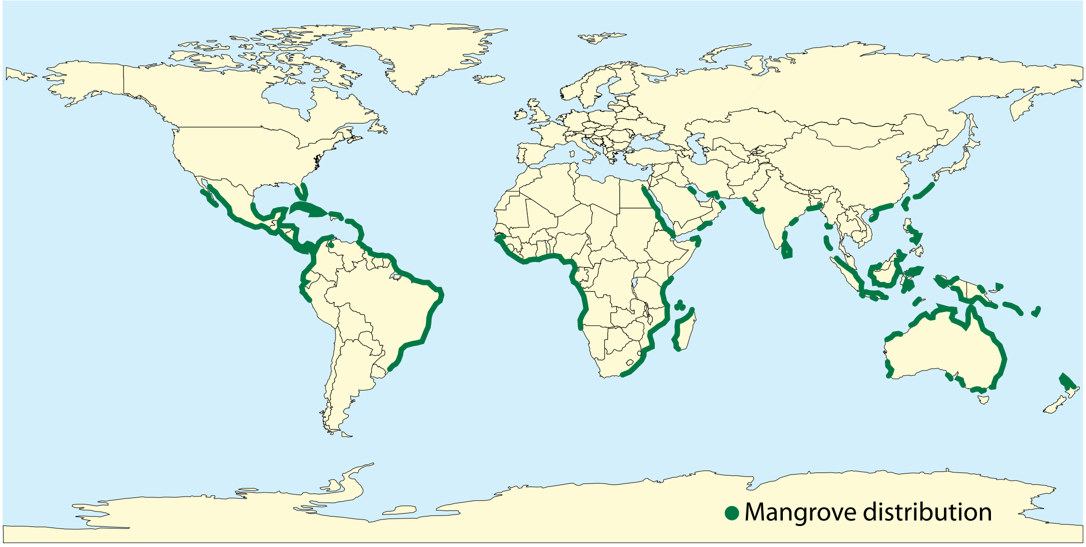
Victor H. Rivera-Monroy and Robert R. Twilley

Mangroves are plant formations usually found in sheltered tropical and subtropical coastlines of Australia, Asia, Africa, and the Americas. They are dominant above mean sea level in the intertidal zone of marine coastal environments between latitudes 31°N and 38°S. Mangroves have been described as "coastal woodlands," "mangals," "tidal forests," or "mangrove forests," with the latter name more commonly used in the Americas, including Florida. Mangroves are considered an ecological assemblage rather than a taxonomic or a morphological grouping.

Mangroves include individuals of various plant families that are adapted to survive the changing and demanding conditions of areas periodically inundated by tides. Thus, mangrove plants grow in soil that is more or less permanently waterlogged and in waters where salinity fluctuates and may be greater than salinity typically found in seawater. Mangrove species share a wide spectrum of morphological, physiological, biogeochemical, and reproductive adaptations that allow them to survive and grow in mangrove habitats. Some of the most critical adaptations include:

1. Foliage salt excretion to remove excess salt from sap;
2. Xerophytic water-conserving leaves to cope with periods of high salinity stress;
3. Buoyant, viviparous propagules to promote dispersal and establishment of new and existing stands;
4. Low water potentials and high intracellular salt concentrations to maintain favorable water relations in saline environments;
5. Exposed breathing roots to grow in anaerobic sediments; and,
6. Support structures of buttresses and aboveground roots to grow with shallow root systems.

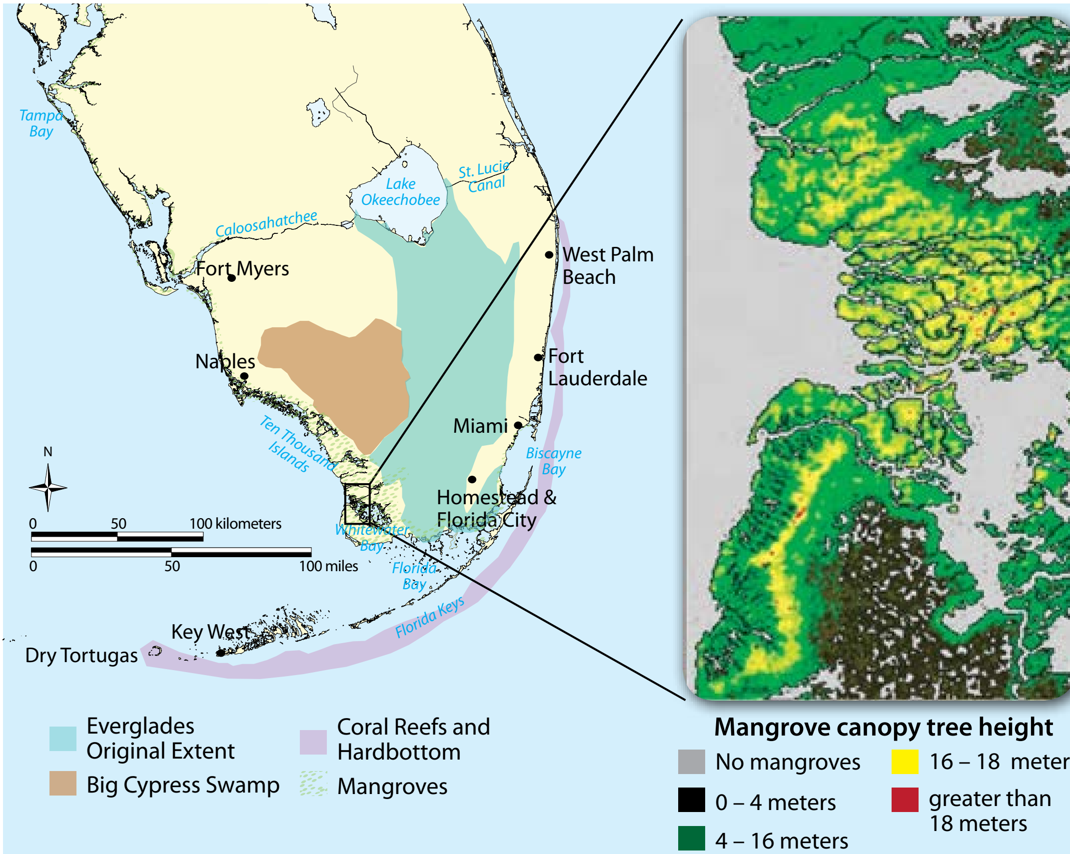
Due to the commonality of these adaptations, wetlands scientists throughout the world recognize approximately 84 species of plants



Adapted from Smithsonian National Museum of Natural History (2010)

Worldwide distribution of mangroves.

Mangrove Habitats



V. H. Rivera-Monroy - LSU

Map of mangrove mean tree height on Gulf coast of Everglades National Park. Most tall mangroves are found near the mouth of Shark River.

belonging to about 39 genera in 26 families as "mangroves." The mangrove trees found in coastal regions of Florida are the black mangrove (Avicenniaceae: *Avicennia germinans*), white mangrove (Combretaceae: *Laguncularia racemosa*), and red mangrove (Rhizophoraceae: *Rhizophora mangle*). Although some species have specific dependence on the coastal habitat, of the 84 species, 63 species are only found in mangrove communities, and 21 species can grow beyond the immediate upper tide levels. It is this wider distribution into nonstrictly mangrove habitat that some species are classified as "nonexclusive" or "associate" mangroves, such as buttonwood (*Conocarpus erectus*) in Florida.

Mangrove tree development is strongly influenced by temperature, tidal and freshwater inundation, and nutrient availability. Mangroves rarely occur outside the 16°C (60°F) isotherm for air temperature of the coldest month, and they thrive in areas where the water temperature exceeds 24°C (75°F) in the warmest months. There are 1444 km^2 (560 mi^2) of mangroves in Florida, mostly in south Florida within the boundaries of Everglades National Park and along the Gulf coast north to Marco Island, including the Ten Thousand Islands. Mangrove areas are limited in other coastal regions of the state; largest areas are found in the Indian River Lagoon on the east coast and the Caloosahatchee, Pine Island Sound, Charlotte Harbor, and Tampa Bay on the west coast.

Three dominant mangrove species are found in south Florida

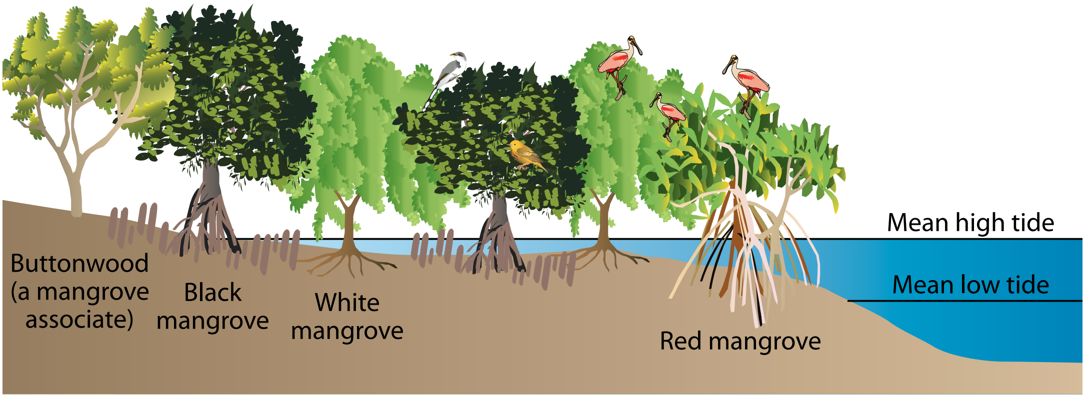
Sharon M. L. Ewe

There are three dominant mangrove tree species in south Florida: red mangrove (*Rhizophora mangle*), black mangrove (*Avicennia germinans*), and white mangrove (*Laguncularia racemosa*). Buttonwood (*Conocarpus erectus*) is often found landward of mangroves and is considered a mangrove associate, not a true mangrove species. Mangrove trees can vary in size, ranging from 0.5 meters to greater than 18 m (1.5 – 60 feet) tall. Mangroves are tallest in areas with strong tides. Mangroves growing where nutrients are limited, or in areas exposed to limited tidal flushing, can form short, bushy-looking stands less than 1.5 m (5 ft) tall. These are called "scrub mangroves." These trees are dwarf due to a stunted growth form and are not genetically different from the taller trees.

South Florida mangrove species can be distinguished by their leaves, stems, roots, and reproductive structures. Red mangroves are commonly found closest to the water and have reddish stems and arching prop roots, giving these plants the name "walking trees." Red mangroves also have long, pendulous, green propagules that are often visible year-round hanging from tree branches.

Fertilization of scrub red mangroves with phosphorus (right) can result in their rapid growth (left).

These reproductive structures take almost two years to develop to maturity and are actually young growing seedlings of the plant, a reproductive strategy known as vivipary. Further inland, in areas often ponded with high salinity, black mangroves can be found in abundance. This species has very dark bark and numerous pneumatophores that poke like fingers above the soil. Black mangrove



The three dominant mangrove species found in south Florida are the red, black, and white mangrove. Buttonwood is a mangrove associate that is often found at the landward margin of mangrove communities.

pneumatophores help bring oxygen to the roots, and their length can vary from a few centimeters (2 inches) to about 60 cm (2 ft) long. This species is notable in that it has the ability to excrete excess salt from its leaves. On warm, dry days, the excreted salt can be seen as crystals on the surface of the leaves.

White mangroves can be found mixed with other species, but are usually found beyond the shoreline at the upper edge of the tides. White mangroves differ from other mangrove species in that their leaves are slightly flattened at both ends (i.e., oblate). In late summer, white mangroves have copious fruits, about 1 cm (0.5 in) long, hanging from the ends of branches in thick clusters.

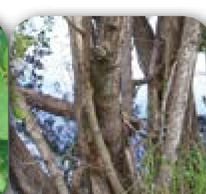
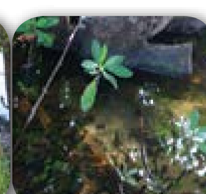
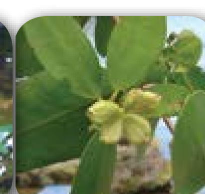
Buttonwoods are found in upland areas away from the water edge. They have spreading crowns, furrowed bark, and pointed leaves. Brownish, round fruits are often found in clusters at the tips of their branches.

A. M. Molina Fletcher

Black mangrove pneumatophores at Whiskey Creek, Broward County, Florida.

Each mangrove species has distinctive features

Sharon M.L. Ewe

	Leaf	Trunk	Root	Reproductive structure
Red mangrove 	 Dark green, opposite, elliptic, 7.5 – 12.5 centimeters (3 – 5 inches) long.	 Reddish brown, bright red inner bark.	 Arch-shaped prop roots from trunk and branches.	 Viviparous propagules can be up to 30 cm (1 foot) long.
Black mangrove 	 Upper surface shiny, lower surface with whitish hairs, oblong, opposite, 5 – 10 cm (2 – 4 in) long, may have salt crust.	 Gray-black with scaly, squarish block-like pattern.	 Finger-like pneumatophores that extend up from roots in the ground.	 Green, flattened bean-like propagules up to 2.5 cm (1 in) in diameter.
White mangrove 	 Opposite, notched at tip, reddish petioles, two glands at base.	 Whitish inner bark.	 May have adventitious roots from base of main stem and small pneumatophores under flooded conditions.	 Ridged, almond-shaped, flattened gray-green drupes less than 2.5 cm (1 in) long.

Images: A. M. Molina Fletcher, P.J. Fletcher - FSG, W.L. Kruczynski - EPA, R. Molina

Many other plants grow in mangrove forests

Thomas J. Smith III

Mangrove ecosystems are known for the dominant tree species found in them. However, there are many more plants growing in mangrove ecosystems than just the mangrove trees. Numerous species of nonvascular plants (e.g., algae, lichens, ferns) and vascular plants (e.g., vines, grasses, sedges, air plants, shrubs, nonmangrove trees) all can be found associated with mangrove trees in Florida and the Caribbean. The occurrence of these mangrove "associates" is dependant on conditions such as the frequency and salinity of tidal inundation, the salinity of the soil water, and the openness of the mangrove forest canopy, which allows increased light to reach the forest floor.

At the lower intertidal end of Florida mangrove forests, algae are commonly found growing on the prop roots and pneumatophores of the mangrove trees themselves. Sea moss (*Bostrychia montagnei*) grows profusely on the prop roots of the red mangroves in many forests. Red algae (*Catenella repens* and *Caloglossa leprieurri*) are also found on mangrove roots. The green alga, *Caulerpa verticillata*, is often found on the peat soils under the forest canopy. *Batophora oerstedii*, another green alga, can be found clustered on mangrove roots, particularly in the lowest intertidal zones. Occasionally seagrasses, such as *Thalassia testudinum*, *Halodule wrightii*, and *Ruppia maritima*, can be found intermingled among mangroves close to, and along, shallow shorelines.

T.J. Smith III - USGS

Golden leather fern growing in a mangrove community in Everglades National Park.

T.J. Smith III - USGS

This red mangrove tree has a large stem of the mangrove rubber vine entwined around its trunk.

In middle intertidal mangroves, with intermediate to low salinities, the golden leather fern (*Acrostichum aureum*) and the mangrove rubber vine (*Rhabdadenia biflora*) are conspicuous members of the flora. These two species become very abundant following disturbance to the mangrove canopy. They can become so abundant that they crowd out mangrove seedlings and slow the recovery of disturbed forests.

In higher intertidal areas with less frequent tidal inundation and higher salinities, plants such as saltwort (*Batis maritima*), sea purslane (*Sesuvium portulacastrum*), glassworts (*Salicornia* spp.), fleabane (*Pluchea odorata*), salt marsh grasses (*Spartina*, *Distichlis*), and salt marsh rushes (*Juncus* spp.) may be found among the mangroves. Air plants (*Tillandsia* spp.) commonly adorn mangrove branches in this environmental setting as well.

In low salinity upstream areas of the Florida Everglades, numerous plant species can be found intermingled with the three species considered "true" mangroves. These include trees and shrubs like white indigo berry (*Randia aculeata*), swamp bay (*Persea palustris*), false willow (*Baccharis angustifolia* and *Baccharis halimifolia*), cocoplum (*Chrysobablanus icaco*), colicwood (*Myrsine cubana*), and pond apple (*Annona glabra*), to name a few. Vines include salt marsh morning glory (*Ipomoea sagittata*), coin vine (*Dalbergia ecastaphyllum*), gray nickerbean (*Caesalpinia bonduc*), and poison ivy (*Toxicodendron radicans*). Marsh plants that can intermingle with mangroves in low salinity areas include sawgrass (*Cladium jamaicense*), spikerush (*Eleocharis cellulosa*), beak rushes (*Rhyncospora* spp.), and black needle rush (*Juncus roemerianus*). In these areas with low salinity and long hydroperiod, algal mats, known as periphyton, often grow among the roots of the mangroves. Throughout these various types of mangrove associations, lichens can be found on the stems of the mangroves and mangrove associates. So, it is easy to see that a mangrove forest is much more than just mangrove trees.

R.A. Howard - Smithsonian Institution

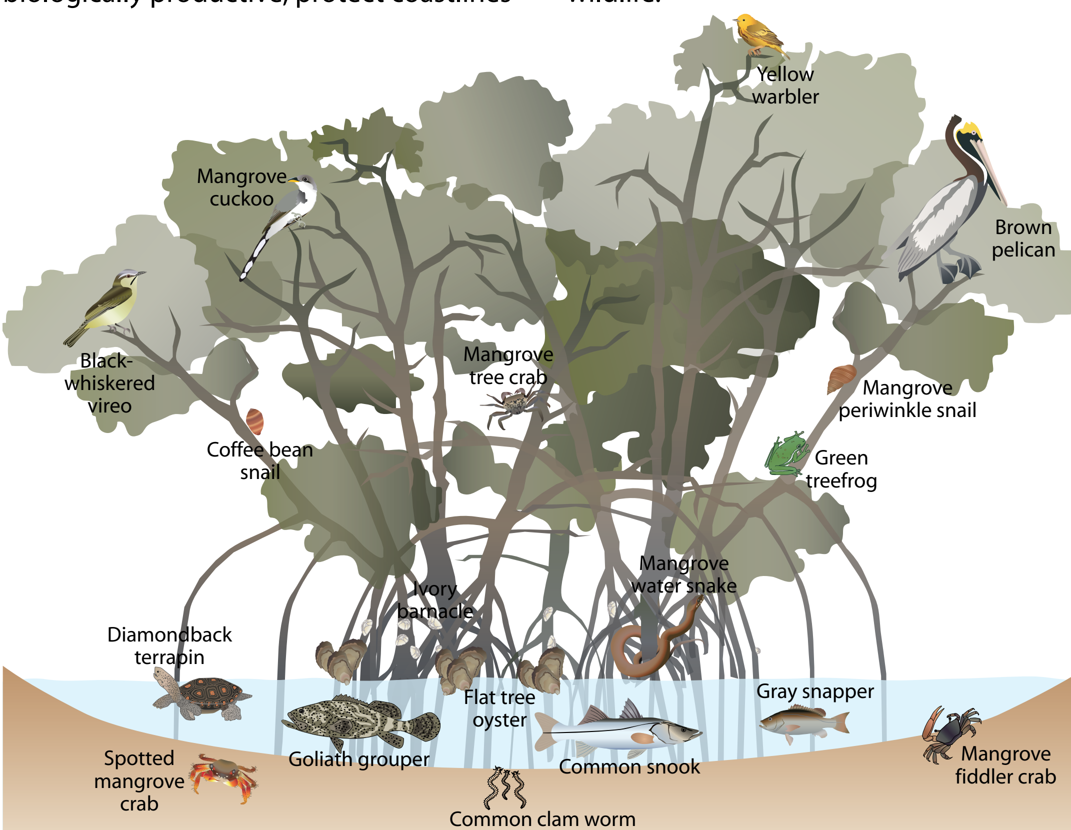
Air plants festoon the branches of buttonwood and white mangrove trees. Other mangrove associates in this photograph are sea purslane and saltwort in the foreground.

Unfortunately, in recent years additional plant species have appeared in Florida mangroves that do not naturally belong there. These introduced or exotic plants include the nonmangrove species, such as Australian pine (*Casuarina equisetifolia*), Brazilian pepper (*Schinus terebinthifolius*), and the Japanese climbing fern (*Lygodium japonicum*). These species are most commonly found along mangrove edges. Several species of true mangroves that are native to the Indo-West Pacific have also been introduced. The orange mangrove (*Bruguiera gymnorrhiza*) and the Asian black mangrove (*Lumnitzera racemosa*) are both growing among native mangroves in northern Biscayne Bay. Invasive exotic plants have the potential to replace native species, alter ecosystem structure, and change the manner in which nutrients cycle in the natural system. For these reasons, control or removal of the exotics may be warranted. Many resource management agencies and organizations in south Florida are taking steps to eradicate these plants before they become major problems to our native mangrove forests.

Many animals live in mangroves

Kevin R.T. Whelan and Jonathan G. Moser

An uninformed observer may view a mangrove forest as a smelly, muddy place that is full of mosquitoes. While that is a pretty accurate description, mangrove forests are coastal sentinels in the subtropics and tropics. They are biologically productive, protect coastlines from erosion, provide detritus to nearby waters, help protect other nearby marine communities by filtering nutrients from water, and are home to a myriad of animal life. From their canopy to their complex root system, mangrove forests teem with wildlife.



Mangrove forests provide habitat to many species of animals. This diagram depicts some of the more notable species. Neotropical migratory birds use the mangrove canopy as a resting and feeding station during spring and fall migrations. Other birds are year-round residents that are wholly dependent on the mangroves for food, shelter, and reproduction, such as the mangrove cuckoo (*Coccyzus minor*). Many animals live in specific parts of the mangrove trees, and there are both vertical and horizontal distributions of habitats in the mangrove forest. Canopy specialists, such as the black-whiskered vireo (*Vireo altiloquus*), feed on the numerous insects that are found among the mangrove leaves. Brown pelicans (*Pelecanus occidentalis*), double-crested cormorants (*Phalacrocorax auritus*), herons, and egrets build their nests in the canopy. Mangrove tree crabs (*Aratus pisonii*) are mostly plant eaters and migrate up and down the mangrove trees looking for their next meal. The prop roots of red mangrove trees are home to the elusive but beautiful mangrove water snake (*Nerodia fasciata compressicauda*). The waters under the mangrove forest teem with fish life, including juvenile goliath grouper (*Epinephelus itajara*), gray snapper (*Lutjanus griseus*), and common snook (*Centropomus undecimalis*). Mangrove forests have a complex food web in which the nutrients from the mangrove leaves are not readily available. The leaves are first processed by bacteria and yeasts which form detritus. The detritus food system supports many species, such as mangrove fiddler crabs (*Uca thayeri*), amphipods, isopods (i.e., microcrustaceans), and marine worms (*Alitta succinea*) that are then fed upon by fish and wading birds.

Mangroves can be classified into five distinct forest types

Carlos A. Coronado

The classification scheme of mangrove forest types is based upon species dominance, appearance, and zonation, which are closely linked to local topography and hydrology. Based on those factors, the mangrove forests of Florida and the Caribbean have been classified into five forest types: fringe, overwash, riverine, basin, and scrub (dwarf). Several geographic settings in the tropics and subtropics favor the development of mangrove forests, including shallow bays, estuaries, and lagoons that are adequately protected from wave action. The range and duration of tidal flooding is also an important determinant of the type, extent, and ecological functions of these mangrove forests. Exotic trees such as Brazilian pepper (*Schinus terebinthifolius*) and Australian pine (*Casuarina* spp.) are often found in disturbed mangrove forests.

Fringe mangrove forests

These occur along the edges of protected shorelines and along canals, rivers, and lagoons. This forest type is commonly observed along shorelines where the elevation is higher than the mean high tide, but the forest is exposed to daily tides. Red mangrove trees dominate fringe forests, but other mangrove species may be found. Due to the damping of tidal energy and waves within their well-developed prop root system, there is often an accumulation of organic matter in fringe forests. Fringe forests are most affected by natural disturbances, such as storms, strong winds, and hurricanes.

M. Stone

Fringe mangrove forests are dominated by red mangroves and are exposed to daily tides.

Overwash mangrove forests

These occur on relatively small, low islands and finger-like projections of land that are completely inundated on a daily basis during high tides. Incoming tidal energy carries away loose organic debris and leaf litter into open water. Some classification schemes consider overwash forests as a special case of the fringe forest. Because the water surrounding the islands acts as a barrier to predatory animals, such as raccoons, rats, and feral cats, overwash mangrove forests are often the site of bird rookeries.

P.J. Fletcher - FSG

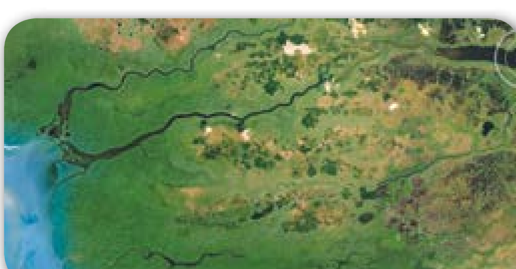
Overwash mangrove forests are completely inundated daily by high tides and are often the site of bird rookeries, such as this one in Card Sound.

Riverine mangrove forests

This forest type is dominated by red mangroves and is the most productive of the mangrove community types. Even though this forest type occupies an elevated topographic zone adjacent to flowing water, it is flushed daily by tides. Riverine mangrove forests occur on seasonal floodplains in areas where

Riverine mangrove forests in Shark River are very productive as a result of nutrients delivered during periods of high freshwater flow.

natural patterns of freshwater discharge remain intact. Salinity drops during the wet season, when rains cause extensive freshwater runoff; however, during the dry season, estuarine waters are able to intrude more deeply into river systems, and salinity increases as a result. This alternating cycle of high runoff/ low salinity followed by low runoff/ high salinity is responsible for the high productivity observed in riverine forests. High seasonal salinity may aid primary production by excluding space competitors from mangrove areas. Furthermore, nutrient availability in south Florida may be increased by alternating the supply of phosphorus from marine waters and nitrogen from the watershed, thus promoting optimal mangrove growth.



Aerial view of extensive red mangrove riverine forest in Everglades National Park near Shark River.

Basin mangrove forests

These mangrove forests occur in inland depressions located behind fringe mangroves and in drainage depressions where water is stagnant or slowly flowing. Basin forests are flooded irregularly by the highest tides. Hypersaline conditions are common, which makes this forest type less productive than fringe or riverine forests. Black mangroves typically dominate basin communities. Basin forests contribute large amounts of organic detritus and dissolved organic matter to adjacent waters.

Basin mangrove forest on No Name Key. Basin forests are typically dominated by black or white mangrove trees. Basin forests are flooded irregularly and often have standing, stagnant water. Hypersalinity reduces productivity in basin forests, but they export tannin-colored dissolved organic matter to adjacent waters.

Scrub (dwarf) mangrove forests

Scrub forests occur in areas where nutrients, freshwater, and tidal inundation are limited. Any mangrove species can be dwarfed, and the trees are generally 1 meter (3 feet) tall or less. Scrub forests are most common in south Florida, but occur in all portions of the geographic range of mangrove trees where physical conditions are suboptimal. Due to their small size, scrub mangroves have lower net primary production relative to other mangrove types.

Scrub (dwarf) red mangrove forest in the back country of the Florida Keys. Other mangrove species can also occur in dwarf forms.

Mangroves provide ecosystem goods and services

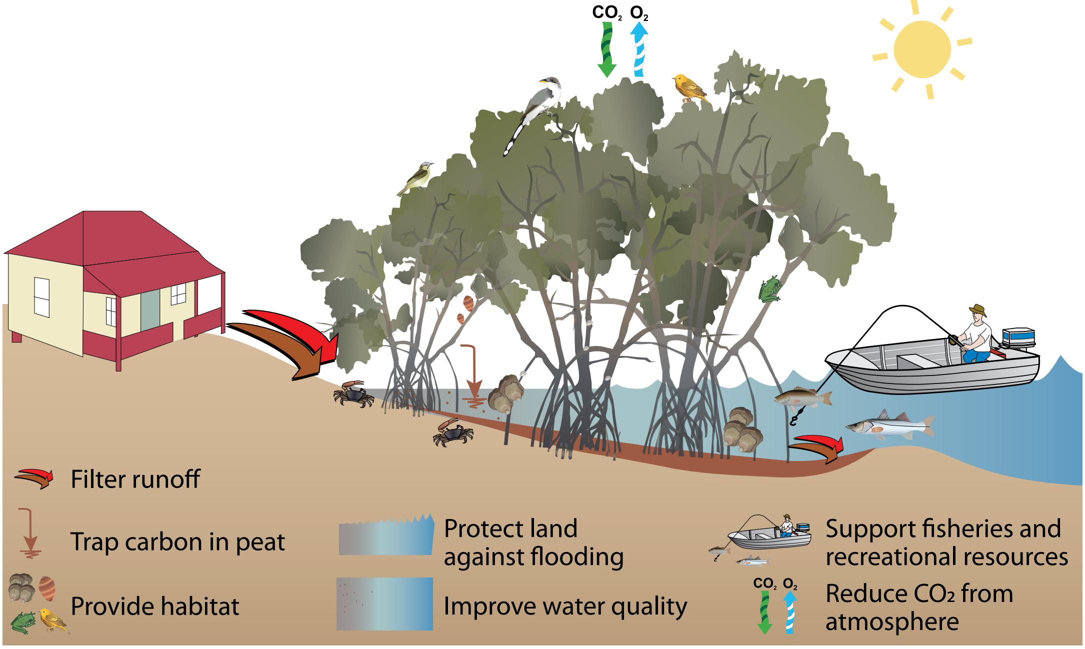
Steven E. Davis III

The goods and services provided to society by wetlands on a per unit area basis is higher than any other terrestrial or marine ecosystem. Losses or degradation of mangrove wetlands result in a direct loss of valuable ecological goods and services provided over a range of spatial and temporal scales. At the local scale, mangrove wetlands are often important in distributing the flow of water from adjacent uplands to open water aquatic ecosystems, thus promoting exchanges of nutrients and other elements among the atmosphere, water column, and soil. This functional attribute also leads to the physical retention of suspended material and nutrients and promotes uptake and exchange of elements, often leading to improvements in water quality. Standing water or saturated soils result in soil anoxia and conditions that are often favorable for long-term trapping (i.e., sequestration) of carbon in the peat soils of these wetlands. This helps to maintain or increase soil elevation in the face of rising sea levels.

Important mangrove goods and services

- Protect shorelines;
- Distribute water flow;
- Improve water quality;
- Build soil elevation;
- Provide habitat and nursery areas;
- Provide cultural and recreational experiences; and
- Help reduce CO_2 in the atmosphere.

As with many wetland types, mangrove forests are known to provide important habitat for aquatic, terrestrial, and arboreal organisms, contribute to recreational and aesthetic values, and serve as nursery areas for many commercially and recreationally



Mangroves provide important ecological functions to the marine environment.

A red mangrove nestled among coastal vegetation provides habitat for animals. Note the prominent galls present on the trunk. The galls are caused by a fungus and are not thought to be harmful to the tree.

important species of fish and crustaceans. Mangrove wetlands also have significant cultural value, particularly in south Florida with its rich Native American history.

Various approaches have been used to place a relative value on the goods and services provided by mangroves. However, the importance of these goods and services is usually recognized only after wetlands have been degraded or lost. For example, wetland loss or degradation due to nutrient enrichment or hydrologic modifications in south Florida has been linked to dramatic changes in bird community composition and nesting success. In central and south Florida, the conversion of wetlands to agriculture and urban areas has been cited for the increased incidence of frost over the last century, underscoring the importance of these aquatic ecosystems in regulating climate patterns. The role of coastal mangrove forests was dramatically exhibited along the coasts of Sri Lanka and India during the Indian Ocean Tsunami in December 2004. Areas with more coastal mangroves experienced significantly less losses due to flooding than developed shorelines. A similar service is provided by mangrove forests in south Florida during the frequent tropical storms and hurricanes.

Mangrove forests are highly productive

Victor H. Rivera-Monroy and Robert R. Twilley

Mangrove forests are among the most productive ecosystems on Earth, and their high productivity strongly affects their ecological and economic significance. Mangroves function as a nutrient and sediment filter between land and sea, contribute to coastline protection, and provide commercial fisheries resources and nursery grounds for coastal fish and crustaceans.

Productivity is a central ecological function in all ecosystems. The total amount of productivity in a region or ecosystem is called gross primary productivity. A certain amount of organic material is used to sustain the life of producers (i.e., respiration), and what remains is called net primary productivity. Net primary productivity is defined as the net flux of carbon from the atmosphere into green plants per unit time. Thus, net primary productivity refers to the amount of plant matter produced per day, week, or year and is calculated and usually reported as grams biomass/m^2/yr. Net primary productivity is the amount of organic material available to support the consumers (herbivores and carnivores) of the ecosystem. Net primary productivity is a critical ecological variable in mangroves because it measures the energy input to the biosphere and the assimilation of terrestrial and marine carbon dioxide. Mangrove net primary productivity is also an important assay in determining the health of the coastal ecosystem.

The area covered by mangrove forests worldwide is about 240,000 km^2 (93,000 mi^2). This represents only a fraction of the total area of tropical forests. However, mangroves occur at the terrestrial-ocean interface and make an important contribution to nutrient cycling in coastal waters. The degree of

V. H. Rivera-Monroy - LSU

Distribution of mangrove forests in Taylor Slough (Everglades National Park) near the northeastern portion of Florida Bay. Differences in tree densities and net primary productivity reflect availability of nutrients and differences in hydrology.

organic matter retention and nutrient processing by mangroves can vary considerably depending upon factors such as their position in the landscape (i.e., geomorphology), tidal amplitude (i.e., hydrology), local climate, vegetation type, and other biotic influences. For example, the number of crabs in the leaf litter is an important component of turnover of organic matter.

Many mangrove forests in south Florida grow on top of carbonate limestone, which constrains forest net primary productivity. This limestone base tends to immobilize phosphorus, limiting its availability for plant growth. Nitrogen may also be a limiting nutrient in many Florida coastal environments. Limiting nutrients and hydrology differences can result in conspicuous differences in mangrove tree densities and net primary productivity.

Most productivity studies have focused on aboveground net primary productivity (e.g., leaves, stems, prop roots) rather than belowground (e.g., soil roots) due to technical difficulties in measuring soil root biomass for individual tree trunks. Recent comparative studies of aboveground net primary productivity rates in the Everglades region of south Florida shows that mangroves growing in the eastern region (e.g., Taylor Slough) are characterized by lower net primary productivity values (340 grams of biomass per meter squared per year) compared to mangroves growing on the southwestern coast (e.g., Shark River) (2208 g biomass/m^2/yr), where the tidal flushing and energy is very high. Aboveground net primary productivity values from Florida are similar to values reported from Puerto Rico (1256 g/m^2/yr), Thailand (2670 g/m^2/yr), and Indonesia (2290 g/m^2/yr). Seasonal litterfall, including leaves, wood, and plant reproductive parts, is highest during the wet season. Litterfall provides organic matter (detritus) to neighboring waters and contributes peat and nutrients to mangrove soils. Any changes in hydrology (e.g., tides, freshwater discharges), either human-induced or natural, can affect long-term spatial and temporal patterns of productivity.


R. Molina

Seasonal litterfall shown in the shallow water provides organic matter to neighboring waters and contributes peat and nutrients to mangrove soils.


R. Molina

Mangroves live in a wide range of environmental settings. The red mangroves shown here are growing in the Lower Keys.

Mangroves provide habitat for many species of interest

Kevin R. T. Whelan and Jonathan G. Moser

Mangrove forests are among the most threatened habitats in the world. Growing in the intertidal areas between land and sea, mangroves provide critical habitat for a diverse marine and terrestrial flora and fauna. Healthy mangrove forests are a critical component of the ecological integrity of the south Florida marine ecosystem.

Mangroves provide critical habitat for a variety of protected species, such as the federally endangered smalltooth sawfish (*Pristis pectinata*) and the threatened American crocodile (*Crocodylus acutus*). Mangroves are home to many species for their entire life cycle. For others species, mangroves are critical to specific stages of the animal life cycle and for foraging and nesting.

Nursery habitat

The smalltooth sawfish uses the mangrove shoreline community as a nursery habitat. Acoustic radio tracking of small juvenile smalltooth sawfish indicates extensive utilization of red mangrove prop roots for predator avoidance. Additionally, juvenile smalltooth sawfish inhabit the greater mangrove shoreline community along shallow bays and river mouths.

Foraging habitat

Silver rice rats (*Oryzomys argentatus*) are a federally endangered species. They forage in mangroves for isopods (*Ligia* spp.), snails (*Melampus* spp.), crabs (*Uca* spp.), seeds of saltwort (*Batis maritima*) and buttonwood (*Conocarpus erectus*), red mangrove (*Rhizophora mangle*) propagules, and germinating black mangrove (*Avicennia germinans*) seedlings.

The yellow-billed cuckoo (*Coccyzus americanus*) is one of many species of birds that use mangrove habitats as a "stopover" during spring and fall migrations. Populations of the yellow-billed cuckoo are declining through its range.

Nesting habitat

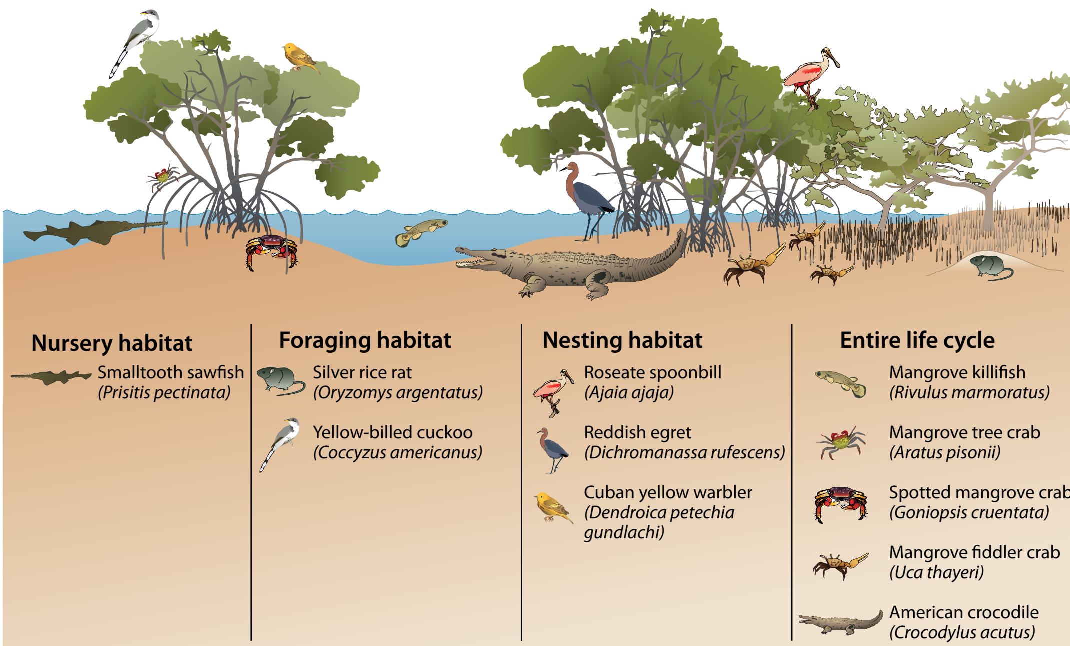
American crocodiles construct nest mounds in back bays along mangrove shorelines. This habitat is considered so critical to crocodile survival that the United States Fish and Wildlife Service established the Crocodile Lake National Wildlife Refuge in northern Key Largo to protect their breeding and nesting grounds.

The majority of the roseate spoonbill (*Ajaia ajaja*) nests are constructed on mangrove islands in Florida Bay. They prefer to build their nests in dense red mangrove forests hidden from view. Roseate spoonbills prefer to breed near areas that are well suited for feeding and will often alter where they nest when foraging habitats become disturbed. As a result of the roseate spoonbill nesting dependence on mangroves, the South Florida Water Management District and Miami-Dade County have acquired nearly 50% of the remaining mangrove habitat south of Florida City and east of U.S. Highway 1.

T. Wilmers - USFWS

Reddish egrets, a State Species of Special Concern, use mangroves for nesting and roosting.

Mangrove Habitats



Mangroves provide critical habitat for a variety of animals. The canopy, branches, and roots support different life stages of the animal life cycles, including foraging and nesting areas.

The reddish egret (*Dichromanassa rufescens*) is a species of concern due to continued low numbers as a result of harvesting of the colorful plumage during the late 1800s. The reddish egret is a rare wading bird that nests in Florida Bay year-round. It forages in the shallow, high saline waters around the mangroves for aquatic invertebrates and small fish. The Cuban yellow warbler (*Dendroica petechia gundlachi*) is present in the Florida Keys during most of the year. It nests strictly in forked tree branches of mangroves. Typically, both sexes participate in nest construction.

Entire life cycle

The mangrove killifish (*Rivulus marmoratus*), also known as the mangrove rivulus, relies exclusively on mangrove habitat. It is capable of surviving in areas where few other fish species can exist and can survive in moist detritus for up to 60 days during periods of drought, anaerobic stress (i.e., low oxygen content), or high sulfide conditions. Capillaries in the fish skin are used for gas exchange during harsh times. The mangrove killifish is also unique because it is a self-fertilizing hermaphrodite; that is, both the eggs and the sperm are produced by one parent, and the young are genetically identical to the parent. Human activities, such as impounding marshes and mangroves for mosquito control and cutting down or severely trimming mangroves, have contributed to habitat loss for the mangrove killifish. Its continued survival depends on healthy mangrove forests.

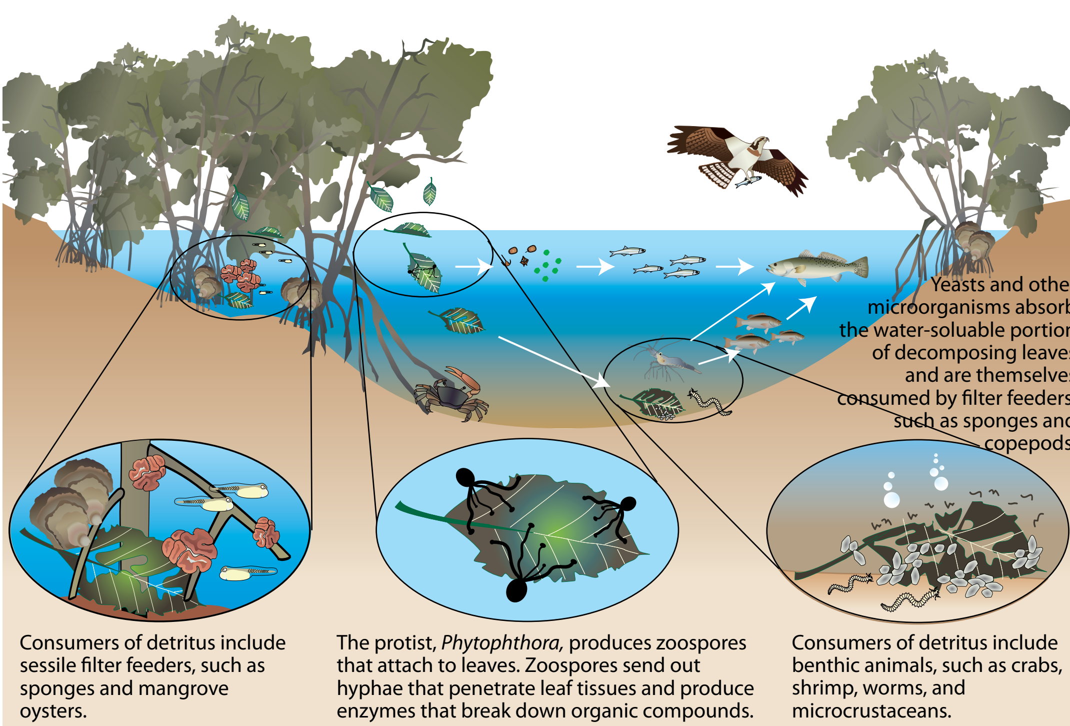
Several species of crabs spend their entire life cycle among the mangroves. The mangrove tree crab (*Aratus pisonii*) spends most of its time in the canopy of red mangroves, where it feeds on leaves and propagules. The spotted mangrove crab (*Goniopsis cruentata*) also lives among the red mangroves, climbing in the tree and around the prop roots. The mangrove fiddler crab (*Uca thayeri*) lives below the mangrove canopy and builds tunnels in the sediments. Crab tunnels are important for oxygen exchange and nutrient content of the soil and water. These crabs all perform important roles in the mangrove community and are critical to the long-term survival of the mangrove ecosystem.

Microorganisms are an important component of the mangrove food web

Jack W. Fell

Mangrove forests are unique ecological environments that provide habitat and nursery areas for a variety of invertebrates and fishes. The forests are among the most productive in the world based on their production of carbon. Carbon also comes from several other sources: phytoplankton in the water, benthic algae, and seagrasses that are swept shoreward and then become entrapped among the mangrove roots. Mangrove leaf litter is a large contributor to the carbon pool. This carbon becomes available to animals, including commercially and recreationally important species, through a variety of pathways. The conversion of leaf litter into a protein-enriched food source is a complex process mediated by microorganisms (e.g., bacteria, fungi, protists) that act individually and in concert.

The microbes work on two fractions of the leaf litter, the solid portion of the leaf and the soluble component that leaches from the decaying leaf. Within minutes after a leaf hits the water, the leaf is attacked by swimming zoospores of fungal-like protists of the genus *Phytophthora*. These protists are closely related, and function in a manner similar, to terrestrial species of *Phytophthora*, which were responsible for the potato blight and famine in Ireland and Europe during the 1800s. In contrast to inciting a plant disease, *Phytophthora* is beneficial as an initial decomposer of mangrove leaves. The zoospores attach to a leaf, encyst, and send radiating hyphae into the leaf. These hyphae contain enzymes that break down the simple and complex carbon compounds in the leaf. Fungi play a similar role, although their spores do not

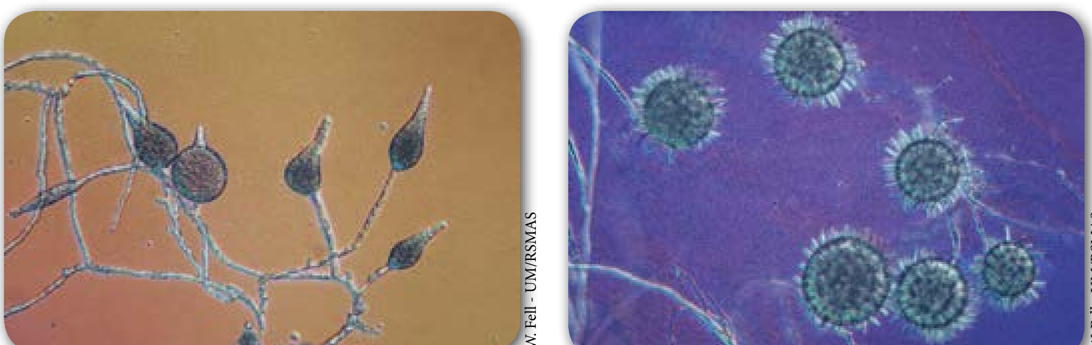


Microbial food web of the mangrove forest.

swim, but float in the water then attach to the leaf, and produce penetrating hyphae and enzymatic activity. *Phytophthora* has an interesting mode of dispersal. They produce large cells, known as a sporangia, which are filled with zoospores. Masses of these zoospores are released from the sporangia to attack other leaves.

Microbes probably work together to produce the protein-rich leaf detritus. The leaf consists mostly of carbon, with sparse amounts of nitrogen in either the leaf or surrounding water. A major source of nitrogen is thought to be provided by nitrogen-fixing cyanobacteria that live on the surface of the leaf. These bacteria produce excess amounts of nitrogen, which is used by the protists and fungi. The resulting nitrogen- and nutrient-rich microbial cells, which are imbedded in the fragmenting leaf, are a valuable food source for animals that feed on detritus.

The water soluble portion of the leaf is also consumed by microbes. For example, yeasts, which are unicellular fungi, are often used as a source of vitamins, minerals and proteins for humans. Yeasts have a similar value in the mangrove ecosystem. Yeast cells convert the organic compounds in the water to nutrient-rich cells, which are consumed by filter feeding benthic animals and zooplankton. The mangrove food web, therefore, initiates with the conversion of plant produced carbon compounds to microbial protein, which is consumed by small invertebrates, which in turn are fed upon by larger organisms in the food chain.



There are several species of *Phytophthora* associated with mangrove leaf decomposition. Two examples are: Left: *Phytophthora epistomium*, the large cells are sporangia that contain zoospores. (Note the hyphal strands that penetrate and infuse through the decaying leaf tissue and release enzymes that break down complex leaf carbon compounds.) Right: *Phytophthora spinosa* have spiked sporangia.

The bottom two figures illustrate the release of flagellated swimming spores. In the left figure, spores are packed in the sporangium and swim out through a pore. In the right figure, the spore has a larger plug that is forcefully ejected (far left), followed by a burst of swimming spores, which rapidly attach to fallen and submerged mangrove leaves to initiate the decomposition process.

Natural disturbances alter the structure and function of mangrove forests

Thomas J. Smith III and Kevin R.T. Whelan

Natural disturbances are common in mangrove forests in Florida and throughout the world. These disturbances occur at a variety of scales, ranging from meters to thousands of kilometers. The agents of disturbance are varied, but include insect outbreaks, lightning strikes, high winds (e.g., thunderstorms, hurricanes), storm surges, and winter cold fronts, to name a few. In the Florida Everglades, fire is also important in upstream areas where mangroves border marshlands. The most studied disturbances in Florida mangroves are effects from lightning strikes and hurricanes.

Thunderstorms are common in Florida, occurring year-round, and the state has been called "the lightning capital of the world." When lightning strikes in a mangrove forest, the electrical energy passes through the struck tree to the surrounding trees, resulting in the death of a group of trees rather than a single individual. The gaps vary in size from about 100 m^2 (119 yd^2) to over 1000 m^2 (1196 yd^2). There can be hundreds of gaps in 1 km^2 (0.39 mi^2) of forest.

These gaps are important to the ecology of the mangrove forest. Within gaps, sunlight penetrates to the forest floor, and gaps serve as places where seedlings can become established and grow quickly. Most of the mangroves in the world are gap dependent to some extent. The white mangrove (*Laguncularia racemosa*) is probably the most gap dependent of the three species of mangrove in Florida. Depending on which species gets into the gap first, it is possible to change the local species composition. For example, if red mangroves (*Rhizophora mangle*) dominated a small patch that was hit by lightning and killed, either white mangroves or black mangroves (*Avicennia germinans*), or both, might colonize the gap first and become the new dominant species in that local area. This process is referred to as "gap dynamics" by forest ecologists, and it occurs in all of the forested ecosystems worldwide, not just mangrove forests.

T.J. Smith III - USGS

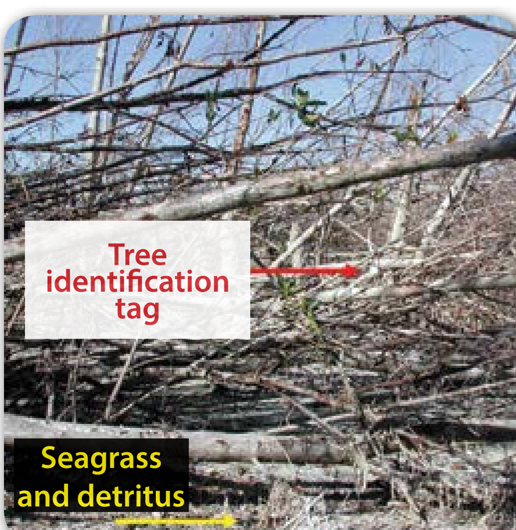
Aerial photograph showing a landscape-scale view of gaps in the mangrove forest canopy along the lower Shark River in Everglades National Park. All of the dot-like features are gaps in the canopy. The darker dots (red arrows) are older gaps, and the lighter gray dots (yellow arrows) are younger gaps.

T.J. Smith III - USGS

This oblique aerial photograph shows a close-up of a newly created lightning gap in the mangrove forest of Everglades National Park.

Hurricanes impact a far greater area than a lightning strike. South Florida has been struck by numerous hurricanes since 1900, including more than 20 major storms (Category 3 or above on the Saffir-Simpson scale). Hurricane impacts include effects from high winds, storm surges, and often torrential rain that can add to the flooding. Additionally, the surge may carry sediment that may be deposited on the mangrove forest floor. Wind and surge effects can devastate mangrove forests that exist along the coast. Mortality often reaches 100% of the stems. Sometimes, small stems survive better than larger stems. Following Hurricane Andrew (1992), scientists noted that small mangroves growing in lightning-created gaps often survived better than the adult stems that surrounded the gap. Thus, small-scale disturbances (e.g., lightning) may aid in recovery from large-scale disturbances (e.g., hurricanes).

The effects of sediment deposition in mangroves depend on the depth and type of sediment deposited. Deep deposits of clay and silt can effectively block the ability of mangrove breathing roots to take up oxygen, thus suffocating the trees, as occurred in some areas of southwest Florida following both Hurricanes Andrew and Wilma. Following Hurricane Wilma (2005) most deposits were relatively shallow (less than 10 centimeters [4 inches]), and they had no negative impacts on the forest vegetation. Nutrients in sediments may have a beneficial effect on plant growth.



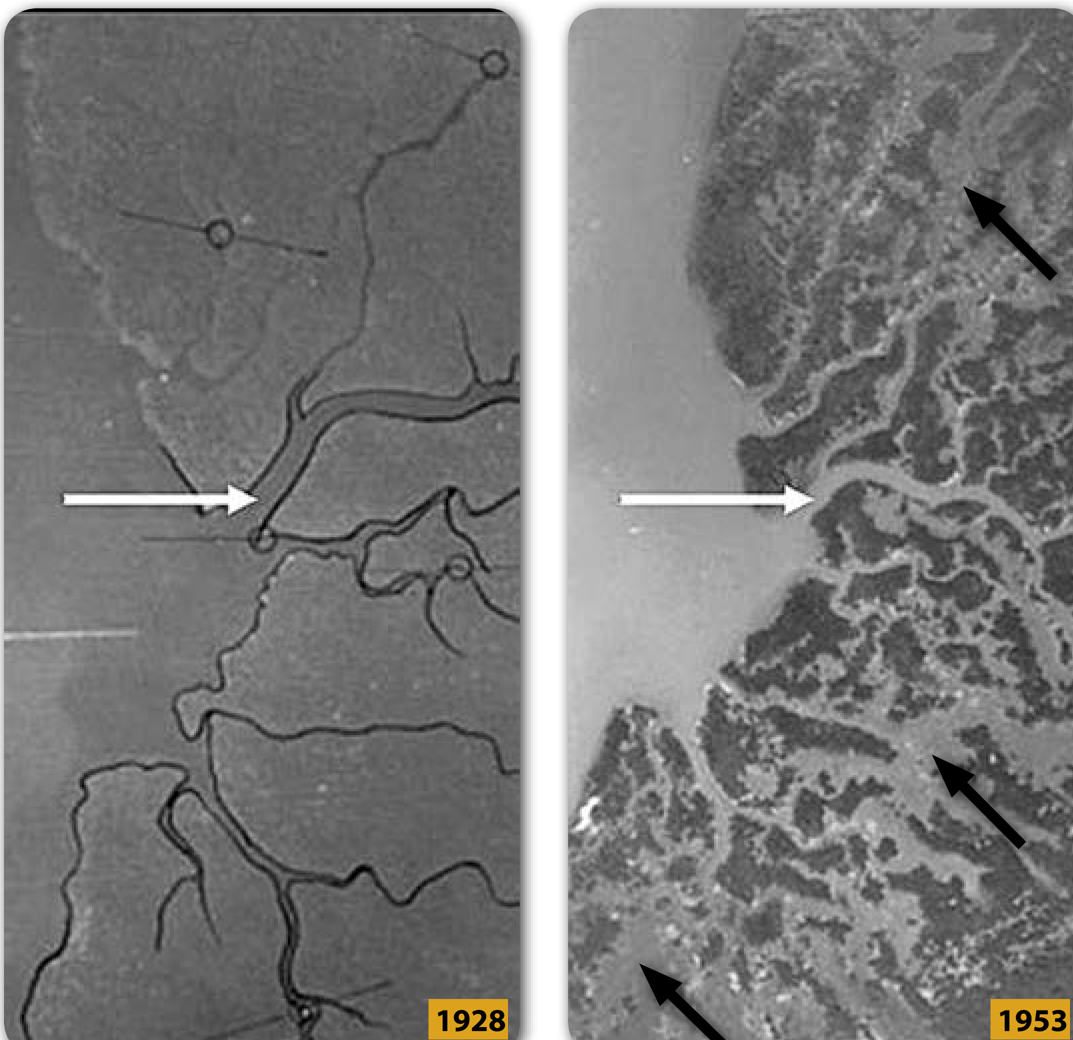
T.J. Smith III - USGS

The remnants of a U. S. Geological Survey study plot in Everglades National Park after the passage of Hurricane Wilma (2005). The red arrow points to a tree identification tag that somehow survived the hurricane. The yellow arrow points to seagrasses and sediment that were swept inland by the storm surge. This plot is 150 m (490 ft) inland from the shoreline. There has been no recruitment of new mangroves into the plot.

T.J. Smith III - USGS

Mangrove seedlings are abundant in the high light environment of a canopy gap. The species composition within gaps depends upon which species colonizes the gap first. This process is called "gap dynamics."

Recovery of the mangrove forest following large-scale disturbance from hurricanes is not a sure thing. Hurricane Wilma struck forests that had been severely impacted by Hurricane Andrew 13 years previously. The area affected by both storms was large and damage was very widespread. In many of the mangrove research plots maintained by the U. S. Geological Survey, there has been no recruitment of new stems since the passage of Wilma. Examination of historical aerial photos indicates that hurricanes are in fact capable of causing a change in ecosystem types. An example is the Big Sable Creek area of Everglades National Park. Prior to 1928, mangrove trees lined the creek in this region, coming to the edge of the creek-banks. By 1953, extensive mud flats were present. In the interval between, this area was hit by three major hurricanes. Two Category 3 storms impacted the region, one in 1929 and one in 1948. In 1935, the great "Labor Day" hurricane crossed Cape Sable. It was the first Category 5 storm to hit Florida since record keeping began. Clearly, some mangrove forests cannot withstand repeated impacts from large hurricanes. Scientists are studying ways to assist in forest recovery and restoration following large disturbances.



From Smith et al. (2009); used with permission from Wetlands

Aerial photographs of the Big Sable Creek area in Everglades National Park. White arrows show mouth of creek. Photograph on the left was taken in 1928 (U.S. Army Air Corps for the U.S. Coast and Geodetic Survey). Photograph on right was taken in 1952 by the U.S. Geological Survey (Eros Data Center). The black arrows on the right photograph point to areas of extensive mud flats that formed since 1928 at previously forested areas. Three major hurricanes struck this area and changed the character of the ecosystem. These mud flats persist today.

Human activities can damage mangrove habitats

Sharon M. L. Ewe

Humans have caused the loss of 86% of the mangroves in Florida since the 1940s. Impacts to mangrove forests can be direct impacts, where the forest and plants are immediately affected, or indirect, where the forest species composition and functions are affected secondarily.

Google Earth

Marco Island, FL is a dredge and fill development that destroyed hundreds of acres of coastal mangroves.

Land clearing and filling for development

Because of the high cost of waterfront property, mangrove shorelines have historically been a prime target for development activities. Mangrove trees have been removed and the sites filled and leveled to build roads, waterfront/waterview homes, and businesses.

Dredging activities

Many of the residential canals in south Florida were created by dredging mangrove forests. The adjacent remaining forests were then filled with the dredge spoil to raise the elevation for development. Mangrove forests have also been dredged to create boat channels, marinas, and ports.

Diking and impoundment

Mangrove forests have been impounded to control water levels for flooding and mosquito management. Impoundment changes the flooding depth and duration of mangrove forests and can alter species composition, including increasing the prevalence of invasive exotic species, such as Brazilian pepper, Australian pine, and carrotwood.

Ditching

Mangrove forests have been ditched to drain them in preparation for development and for mosquito control. Mosquito ditches also provide habitat for mosquito fish that eat mosquito larvae.

Harvesting

Mangrove wood was historically used for firewood, charcoal production, and construction materials in south Florida. In Asia, mangrove stems are prized for pier/dock construction because the wood does not rot in water.

Cutting and trimming

Mangrove trees are cut and trimmed by homeowners and developers to provide water views. Because mangroves are a protected community, cutting and trimming has been regulated since 1996

Love your mangroves, do not trim them

- Trimming mangroves from 6.1 m (20 ft) high to a 1.8 m (6 ft) canopy results in the loss of 87% of the annual productivity of that mangrove forest.
- Wildlife value is severely reduced in trimmed mangroves.
- Red mangroves are most sensitive to trimming and can be killed by severe trimming.

in Florida by The Mangrove Trimming and Preservation Act (Laws of Florida 403.9321- 403.9333).

Hydrologic changes

Development adjacent to mangroves, including dredging, filling, and impoundment activities, can change the quantity, quality, and timing of the freshwater and nutrient input into mangrove forests. These activities can also result in changes in tidal flushing of the mangrove forest and change species composition of plants and animals that use this habitat.

Oil spills

Accidental oil spills have the potential of causing significant long-term damage to mangrove habitats. Oil slicks in open waters can be isolated and cleaned up relatively easily, but extraction of spilled oil around mangrove roots is difficult and often destructive. Oil can clog the breathing pores (lenticels) on the prop roots, pneumatophores, stems of the trees, and propagules, resulting in their death. Small oil and gasoline spills from recreational boaters are hard to track because the fuel often disperses quickly into the adjacent mangrove forests. The heavier components of oil can persist in the environment for a long time. Fortunately, there have been few major oil spills in coastal areas of Florida; the last major oil spill occurred in Tampa Bay in 1993 when 121,000 liters (32,000 gallons) of oil were spilled when two barges collided. A 3800 L (1000 gal) spill of diesel oil occurred in Tampa Bay in February 2009.

Runoff and discharges

Sources of discharges into mangrove forests include nonpoint source runoff from roads, residential development, commercial development, and agricultural activities and point sources from wastewater treatment facilities and stormwater outfalls. The primary constituents of immediate concern in runoff and spill events are turbidity, nitrogen, and phosphorus. A nutrient spill will not only have an immediate effect on the water quality and the organisms living there, but also have the potential to cause long-term changes in the structure of the forest by influencing the floral and faunal diversity and species composition of the area. A 30 million L (8 million gal) sewage spill in the Indian River Lagoon in 1999 resulted in an immediate closure of beaches for public health concerns, but little was done to monitor the long-term impacts of the spill on the surrounding mangroves.

Garbage

Human trash and waste in coastal areas is becoming an increasing problem. Mangrove roots are often fouled by garbage that has either been thrown into the water or inadvertently lost from fishing activities and marine traffic. The most common garbage in mangrove forests includes household materials, such as plastic bottles and plastic bags, and recreational and commercial fishing products, such as fishing line, polyethylene trap rope, styrofoam buoys, and crab and lobster traps. Human garbage can affect plant growth patterns and can form physical impediments to the habitat for organisms that live in the mud, such as crabs, clams, oysters, and polychaete worms, and organisms that forage in the mangroves. Although many communities often have "Beach Cleanup Days," mangrove forests are often overlooked because of accessibility and the difficulty of walking through the area.

W.L. Kruczynski - EPA

Trash is becoming an increasing problem in mangrove habitats.

Mangrove Habitats

Sea-level rise compounds the uncertainties facing the future of mangrove habitats

Victor Engel

With the exception of the large contiguous mangrove forests along the southwest coast and on overwash islands, the majority of the remaining mangrove forests in south Florida exist as isolated fragments. In many cases, the remaining mangroves are restricted to a narrow fringe between developed areas and tidal waters. This type of fringing mangrove forest is the most at risk from sea-level rise because of the limited ability to expand inland in these areas. Changes to the historical timing and distribution of freshwater inputs also increase the uncertainty of the long-term survival of this mangrove habitat type.

USGS

Overwash mangrove islands, such as this one in the Ten Thousand Islands, are vulnerable to sea-level rise if accumulation of muds, sands, oyster shells, and organic debris trapped in the roots does not keep up with deepening water depth.

Overwash mangrove islands, such as those in Florida Bay and the Ten Thousand Islands, and those stands at the seaward edge of existing forests, are also at risk from sea-level rise. Current levels of tidal exchange provide nutrients and sediments that help nourish and maintain these communities. Their long-term survival depends upon sediment trapping and peat accumulation keeping pace with sea-level rise. There is evidence that mangrove trees in these locations have not recovered from past hurricane damage. Lack of recovery could be due to the effects of increase tidal amplitudes and flushing of these communities during storms. The extended hydroperiods associated with higher sea levels increase physiological stresses and reduce the ability of mangrove trees to grow and form peat. Higher water levels also can result in more wave action that inhibits recruitment and establishment of propagules and reduces sediment trapping.

Although mangroves might be expected to migrate inland with sea-level rise in areas where there is suitable habitat (e.g., elevation, soils, hydrology), the benefits of this expanded range may be outweighed by the loss of high quality mangrove habitat that currently exists. In addition, inland migration of salt-tolerant mangrove communities will come at the expense of the loss of freshwater systems that they replace.

Perhaps the largest uncertainty of the effects of sea-level rise on mangrove habitats is the response of the mangrove fauna, such as fiddler crabs and mangrove crabs. Many animals that live in mangrove forests play an active role in shaping the communities by excavation of burrows, creation of soil mounds, aeration of soils, and processing leaf litter. The responses of these organisms to sea-level rise is generally not well understood and usually not considered when projecting the effects of sea-level rise on mangroves.

V.H. Rivera-Monroy - LSU

Mangrove fiddler crabs are an important processor of sediments and organic materials in mangrove forests. Impacts of rising sea level on endemic mangrove dwellers are largely unknown.

Mangroves are restored successfully in Key Largo

Jeanette F. Hobbs

The importance of mangrove forests to the quality of life and economic livelihood of south Florida cannot be overstated. Yet the very qualities that draw people to south Florida often place them at odds with mangrove habitats. For example, based on comparisons of aerial photography, it is estimated that the Upper Florida Keys, from Angelfish Key south to Long Key, lost 39.2% of their mangrove forests between 1945 – 1991 due to residential and commercial development. Measures are currently in place to protect and conserve our remaining mangrove habitats, but when impacts are unavoidable, development permits are still issued. Restoration of impaired mangrove habitats is often used to compensate for unavoidable losses (compensatory mitigation).

One such mangrove restoration effort began at Carysfort Yacht Club in North Key Largo in 2001. The 23 hectares (58 acres) tract was developed as a campground and marina, and the restoration project will ultimately result in 12 ha (30 ac) of mangrove and buttonwood transition habitats. The majority of this restoration is being accomplished through the removal of fill that was placed into wetland areas during the development of this property; however, 2 ha (5 ac) of wetland acreage will be restored by placing fill material into a dredged boat basin. The goal of the restoration is to return filled and excavated wetlands to natural, historical elevations.

Portions of the restored areas have been planted with red and black mangroves, while others have been allowed to revegetate naturally from abundant seed sources found nearby. Overall, the survival rate for planted mangroves at this site is 84%. White mangroves have

Mangrove restoration at Carysfort Yacht Club

This restoration project is a cooperative effort, with more than a dozen agencies contributing funding and/or in-kind services. Costs to date have averaged $46,018 per acre restored, or just over $7.00 per cubic yard of fill handled. The ecological benefits of mangrove restoration are well worth the cost of restoration.

Keys Environmental Restoration Fund

Aerial view of Carysfort Yacht Club prior to initiation of restoration activities, 1996.

Keys Environmental Restoration Fund

Aerial view of Carysfort Yacht Club after restoration activities, 2011.

not been planted, but have recruited heavily at higher elevations. Monitoring is being performed to document the success of restoration efforts. To date, four commercially important fish species have been recorded on site, along with 51 species of birds, including reddish egrets, bald eagles, endangered wood storks, and roseate spoonbills. Endangered American crocodiles have also been observed in restored areas.

Carysfort Yacht Basin (2001) immediately after scrape down of fill material to natural grade.

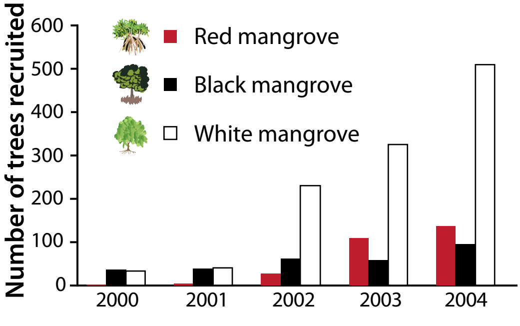
Carysfort Yacht Basin (2007) showing planted group of red mangroves in foreground and natural revegetation.

Mangrove restoration can improve ecosystem health including fish abundance

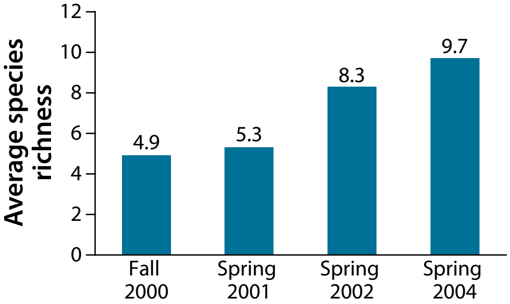
Gary R. Milano

Rapid urbanization and associated coastal development in south Florida over the last 100 years, along with the growing body of scientific evidence documenting the importance of coastal wetlands as habitat and a vital link in the marine food web, has resulted in government regulatory protection of our remaining wetlands and habitat restoration. By the mid 1900s, an extensive network of drainage and flood control canals had been completed in south Florida, which significantly altered how freshwater was delivered to southeastern Florida coastal areas. These regional modifications of freshwater inflow, plus past dredging and filling practices associated with rapid urbanization, caused serious environmental degradation to south Florida coastal wetlands and estuaries.

Biscayne Bay is a shallow, subtropical lagoon on the southeastern Florida coast. Overall, the Bay has lost approximately 45% of the linear shoreline of mangrove wetlands habitat that once bordered it. Recognizing this loss, Miami-Dade County began the Biscayne Bay Wetlands Restoration program in 1987. In the first decade of the program, the Miami-Dade Department of Environmental Resources Management restored and enhanced approximately 121 hectares (300 acres) of coastal wetlands. Four wetland communities have been successfully established utilizing cost effective techniques at 10 coastal sites in Miami-Dade County at a total cost of $6.7 million. The 30 ha (75 ac) wetlands restoration at Bill Baggs Cape Florida State Park is one of the successful mangrove restoration projects in Miami-Dade County.



Natural recruitment of mangrove species from 2000 – 2004.



Number of fish species (i.e., species richness) in created tidal pools from fall 2000 to spring 2004.

To illustrate the efficacy of the restored wetlands habitat at the Bill Baggs site, vegetative monitoring was conducted to document mangrove percent survival, growth rates, natural recruitment of mangroves, and numbers of fish, invertebrates, and bird species.

The tidally connected wetlands were planted with red mangroves on 1.0 meter (3.0 feet) centers utilizing the construction contract and volunteers. White and black mangroves were not planted and recruited naturally into the site through the newly created tidal creeks. The vegetative monitoring revealed an 82% survival of the planted red mangroves after a 5-year period.

Fish monitoring in the 28 created shallow tidal pools demonstrated that 29 fish taxa now use the site. The presence of snook, gray snapper, sailors choice, blue-striped grunt, and commercially important invertebrate species (e.g., blue crab, shrimp) indicates that the restoration area is functioning to support species of recreational and commercial value.

You can help protect mangroves

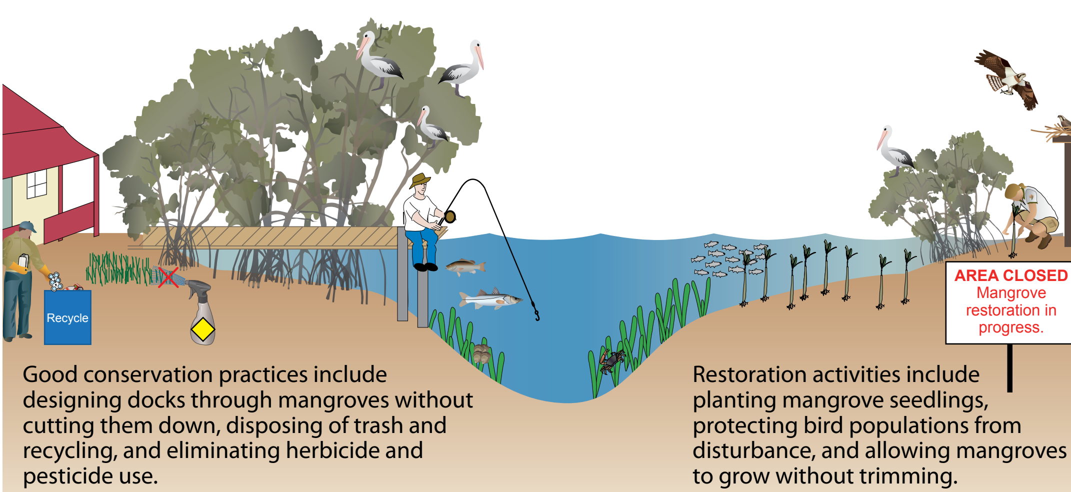
Nancy Diersing and Sharon M.L. Ewe

Mangroves are more than trees that can live in water. They create habitat for marine, estuarine, and terrestrial animals and plants, including a variety of crabs, oysters, shrimp, sponges, fish, reptiles, and birds. They protect shorelines from erosion, help maintain nearshore water quality, export nutrients to other ecosystems, and support marine food chains that help sustain economically valuable fisheries for spiny lobster, snook, tarpon, gray snapper, redfish, and oysters.

Globally, approximately 35% of mangrove forests have been lost to development in the last 20 years. Urban, industrial, and agricultural development has led to the loss or degradation of approximately 86% of the original mangrove wetlands in Florida. Fortunately, vast expanses of mangrove wetlands have been preserved in Everglades and Biscayne National Parks, Florida Keys National Marine Sanctuary, and in many other parks and refuges in Florida. Mangroves are also protected by state and federal permitting programs (Florida Department of Environmental Protection and U.S. Army Corps of Engineers). Both agencies have levied fines for illegal destruction of mangroves and used the funds to restore lost habitat. The Florida Mangrove Trimming and Preservation Act (1996) regulates tree trimming practices and prohibits the use of herbicides in mangrove forests.


A. Molina Fletcher

Mangroves contribute to shoreline stabilization.



Mangrove conservation and restoration increase the survival of mangrove forests.

Good practices conserve mangroves

- Design docks and other structures through fringing mangrove shorelines without harming them.
- Trim minimally to maintain productivity and habitat value. Enjoy your untrimmed mangroves.
- Reduce or eliminate use of pesticides and herbicides on lawns and landscape plants. Chemicals can run off into adjacent waters or wetlands and enter food chains.
- Use biodegradable "green" household products to keep groundwater and nearshore waters free of harmful chemicals and excessive nutrients.
- Many mangroves are found in protected areas. Know and follow all guidelines, including area closures.
- Respect the plants and animals in mangrove habitats. Do not tie ropes to trees or drive nails into tree trunks.
- Dispose of your trash properly. Remove fishing line or other debris that might entangle wildlife.
- Volunteer to participate in organized cleanup events.
- Stay a reasonable distance away from mangrove islands to avoid disrupting bird life. Mangrove islands are important nesting and roosting areas for eagles, ospreys, egrets, frigate birds, spoonbills, and other birds.
- Support local initiatives to improve treatment and disposal of wastewater and stormwater.
- Join organizations dedicated to mangrove conservation, and support restoration efforts at local parks and shorelines.

Keys Environmental Restoration Fund

Trash accumulates along mangrove shorelines. The Alternative Spring Break Group from Vanderbilt University participated in trash cleanup efforts at this site in Key Largo.

Introduction citations

1. Odum WE, McIvor CC. 1990. Mangroves. In: Myers RL, Ewel JJ (eds.). Ecosystems of Florida. Orlando, FL: University of Central Florida Press. p.517-548. *Detailed review of mangrove forests of Florida, composition, value, and management.*
2. Mildred E. Mathias Botanical Garden, University of California at Los Angeles. Major Types of World Vegetation: Mangal. Available from: http://www.botgard.ucla.edu/html/botanytextbooks/worldvegetation/marinewetlands/mangal/index.html (Cited 22 Feb 2011). *The plant community of a mangrove swamp is commonly termed "mangel."*
3. State University of New York at Stony Brook. Mangals. Available from: http://life.bio.sunysb.edu/marinebio/mangal.html (Cited 22 Feb 2011). *Mangals are assemblages of woody plants known as mangroves.*
4. Odum WE, McIvor CC, Smith III TJ. 1982. The Ecology of the Mangroves of South Florida: A Community Profile. U.S. Fish and Wildlife Service, Office of Biological Service, FWS/OBS-81/24, Washington, DC. *Comprehensive review of the ecology of mangrove forests of south Florida.*
5. Palm Beach County. 2010. Florida's Mangroves: The Walking Trees. Available from: http://www.pbcgov.com/erm/natural/mangroves.htm (Cited 22 Feb 2011). *Three native species of mangrove trees are found in Florida.*
6. Vogelsong C. 2003-2009. Ecosystems: Mangroves. Pinellas Chapter of the Florida Native Plant Society. Reprinted from The Understory, August - September 2005. Available from: http://pinellas.fnpschapters.org/mangroves.html (Updated 19 Aug 2009; cited 22 Feb 2011). *Buttonwood is a mangrove associate that does not have true mangrove adaptations but is highly salt tolerant.*
7. Odum EP. 1971. Fundamentals of Ecology. Philadelphia, PA: W.B. Saunders Co. *Mangroves often reach their greatest height and areal extent in low areas with large tidal ranges (tidal subsidy).*
8. Lewis III RR, Gilmore Jr. RG, Crewz DW, Odum WE. 1985. Mangrove habitat and fisheries resources of Florida. In: Seaman W (ed.). Florida Aquatic Habitat and Fishery Resources. Kissimmee, FL: American Fisheries Society, Florida Chapter. p. 281-336. *Five mangrove community types are distinguished based upon periodicity of tides, seasonal terrestrial runoff, species composition, and geographic setting.*
9. Lugo AE, Snedaker SC. 1974. The ecology of mangroves. Annu Rev Ecol Syst. 5:39-64. *Description of mangrove community types.*
10. Ewe SE, Childers DL, Gaiser EE, Iwaniec D, Rivera-Monroy VH, Twilly RR. 2006. Spatial and temporal patterns of above ground net primary productivity (ANPP) in Florida Coastal Everglades LTER (2001-2004). Hydrobiologia 569:459-474. *Comparison of primary producers at Shark River and Taylor Slough.*
11. Lee SE. 1995. Mangrove outwelling: a review. Hydrobiologia 295:203-212. *Review of mangrove forests as sources of organic material to adjacent systems. Dissolved organic material may play an important role.*
12. Smith III TJ, Robblee MB, Wanless HR, Doyle TW. 1994. Mangroves, hurricanes, and lightning strikes. BioScience 44: 256-262. A summary is available from: http://sofia.usgs.gov/publications/papers/mang_hurr_lightning/damage.html (Updated 18 Feb 2005; cited 22 Feb 2011). *Hurricane Andrew caused catastrophic disturbance of the entire west-coast mangrove forest from the Chatham River to Shark Point. In the vicinity of Highland Beach, mangroves were 80-95% destroyed by trunk snapping and uprooting. This damage resulted from wind rather than storm surge.*
13. Odum WE, Johannes RE. 1975. The response of mangroves to man-induced environmental stress. In: Wood EJF, Johannes RE (eds.). Tropical Marine Pollution. Amsterdam: Elsevier Oceanography Series. p. 52-62. *Review of human-induced stresses to mangroves and their responses.*
14. Gilman E, Van Lavieren H, Ellison J, Jungblut V, Wilson L, Areki F, Brighouse G, Bungitak J, Dus E, Henry M, Sauni Jr. I, Kilman M, Matthews E, Teariki-Ruatu N, Tukia S, Yuknavage K. 2006. Pacific Island Mangroves in a Changing Climate and Rising Sea. UNEP Regional Seas Reports and Studies No. 179. United Nations Environment Programme, Regional Seas Programme, Nairobi, Kenya. Available from: http://www.unep.org/PDF/mangrove-report.pdf (Cited 22 Feb 2011). *Estimates of mangroves lost in a changing climate and rising sea level.*
15. Blueline Publishing LLC. 2010. Forests of the Sea: Global Distribution and Dynamics of Mangroves. Imaging Notes, Winter 2010, Vol. 25(1). Available from: http://www.imagingnotes.com/go/article_free.php?mp_id=202 (Cited 22 Feb 2011). *Estimates of acreage of mangroves lost in tsunami-impacted coasts from Landsat data.*
16. Florida Department of Environmental Protection. What are mangroves? Available from: http://www.dep.state.fl.us/coastal/habitats/mangroves.htm (Updated 19 Nov 2010; cited 22 Feb 2011). *Estimates of mangroves lost in some locations in Florida.*
17. Reef Relief Founders. Mangroves: Why they are needed, what threatens them. Available from: http://reefrelieffounders.com/mangroves.html (Cited 22 Feb 2011). *Approximately 60 percent of shallow water mangroves in the Upper Keys were lost between 1965 and 1985; 40 percent of the losses were due to dredging and filling.*
18. Intergovernmental Panel on Climate Change. 2007. Climate Change 2007: Synthesis Report. Available from: http://www.ipcc.ch/publications_and_data/ar4/syr/en/spm.html (Cited 22 Feb 2011). *Projected climate change and its impacts.*
19. Titus JG. 1989. Chapter 7. Sea Level Rise. In: Smith JB, Tirpak D (eds.). The Potential Effects of Global Climate Change on the United States. United States Environmental Protection Agency, EPA-230-05-89-050. p. 119-141. Available from: http://www.epa.gov/climatechange/effects/downloads/rtc_sealevelrise.pdf (Cited 22 Feb 2011). *Global warming could cause sea-level rise of 0.2 to 2 m by 2100. Such a rise would inundate wetlands and lowlands, erode beaches, exacerbate coastal flooding, and increase salinity of estuaries and aquifers.*
20. Lewis RR, Streever B. 2000. Restoration of mangrove habitat. WRP Technical Notes Collection (ERDC TN-WRP-VN-RS-3.2), U.S. Army Engineer Research and Development Center, Vicksburg, MS. 7 p. Available from: http://el.erdc.usace.army.mil/elpubs/pdf/vnrs3-2.pdf (Cited 22 Feb 2011). *Ecological restoration of mangrove habitats is feasible, has been done on a large scale, and is cost effective.*
21. Valiela I, Bowen JL, York JK. 2001. Mangrove forests: One of the world's threatened major tropical environments. Bioscience 51:807-815. *Although mangrove forests, especially in the Americas and Asia, are among the most threatened major environments on earth, this major transformation in the coastal tropics has received little public or political recognition.*
22. Shunnula JP. 2002. Public awareness, key to mangrove management and conservation: the case of Zanzibar. Trees- Structure and Function 16:209-212. Available from: http://www.springerlink.com/content/42fklj6ak1mnnmap/ (Cited 22 Feb 2011). *Awareness of the ecological links between mangrove ecosystems and resources is key to winning management support. The instillation of a sense of*

ownership is an essential component required to achieve full community support for the sustainable utilization and management of common resources.
23. Food and Agriculture Organization of the United Nations. 1994. Mangrove Forest Management. Extracted from FAO Forestry Paper 117. Available from: http://www.fao.org/forestry/mangrove/3650/en/ (Cited 22 Feb 2011). *An argument for developing a multidisciplinary plan to manage mangrove forests.*

Further reading

Booker J. 1997. Mangrove Communities In: Gallagher D (ed). The Florida Keys Environmental Story. Big Pine Key, FL: Seacamp Association, Inc. p. 49-52. *Composition, physiology, productivity, and threats to mangroves in the Florida Keys.*

Bosire JO, Dahdouh-Guebas F, Walton M, Crona BI, Lewis III RR, Field C, Kairo JGa, Koedam N. 2008. Functionality of restored mangroves: A review. Aquat Bot. 89(2):251-259. *Restoration should be based on a functional framework dependent on site conditions. Community involvement and ecosystem level monitoring are integral components of restoration projects.*

Bouillon S, Borges AV, Castaneda-Moya E, Diele K, Dittmar T, Duke NC, Kristensen E, Lee SY, Marchand C, Middelburg JJ, Rivera-Monroy VH, Smith III TJ, Twilley RR. 2008. Mangrove production and carbon sinks: A revision of global budget estimates. Global Biogeochem Cycles 22(2), GB2013, doi:10.1029/2007GB003052. *A comprehensive synthesis of the available data on carbon fluxes in mangrove ecosystems.*

Cannicci S, Burrows D, Fratini S, Smith III TJ, Offenberg J, Dahdouh-Guebas F. 2008. Faunal impact on vegetation structure and ecosystem function in mangrove forests: A review. Aquat Bot. 89:186–200. *Crabs, snails, and insects play a strong role in many aspects of mangrove ecology.*

Davis Jr JH. 1940. The ecology and geologic role of mangroves in Florida. Pap Tortugas Lab Carnegie Inst. 32: 304-412 (Carnegie Inst. Washington Pub. 517). *Classic work on mangrove biology, ecology, and geologic role in Florida.*

Doyle TW, Girod GF, Books MA. 2003, Modeling mangrove forest migration along the southwest coast of Florida under climate change. In: Ning, ZH, Turner RE, Doyle T, Abdollahi K (eds.). Integrated Assessment of the Climate Change Impacts on the Gulf Coast Region. Baton Rouge, La.: Gulf Coast Regional Climate Change Assessment Council and Louisiana State University Graphic Services, p. 211-221. *Computer simulation models of mangrove forest dynamics at the stand and landscape levels were developed to evaluate the impacts of increased water levels and disturbances associated with global climate change on the mangrove forests of the Everglades.*

Duke NC, Ball MC, Ellison JC. 1998. Factors influencing biodiversity and distributional gradients in mangroves. Global Ecol Biogeogr Lett. 7:27-47. *The position of mangrove species in the landscape is often ordered by the interplay of factors along environmental gradients at differing geographic scales.*

Ellison AM. 2000. Mangrove restoration: Do we know enough? Restor Ecol. 8:219-229. *A discussion of problems with mangrove restoration projects and how to improve success rates.*

Fourqurean JW, Smith III TJ, Possley J, Collins TM, Lee D, Namoff S. 2010. Are mangroves in the tropical Atlantic ripe for invasion? Exotic mangrove trees in the forests of South Florida. Biol Invasions 12:2509-2522. *Two species of Indo-Pacific mangrove trees have naturalized in tropical Atlantic mangrove forests in south Florida.*

Hogarth PJ. 1999. The Biology of Mangroves. New York: Oxford University Press. 228 p. *Comprehensive review of the biology of mangroves and factors controlling their distribution.*

Komiyama A, Ong JE, Poungparn S. 2008. Allometry, biomass, and productivity of mangrove forests: A review. Aquat Bot. 89:128-137. *A review of factors controlling the biomass and productivity of mangrove forests.*

Krauss KW, Young PJ, Chambers JL, Doyle TW, Twilley RR. 2007. Sap flow characteristics of neotropical mangroves in flooded and drained soils: Tree Physiol. 27:775-783. *Use of probes to study sap flow in mangrove trees in flooded and drained soils.*

Overpeck JT, Weiss JL. 2009. Projections of future sea level becoming more dire. P Nat Acad Sci. 106:21461-21462. *A prediction of how sea level will change this century and beyond.*

Parkinson RW. 1989, Decelerating Holocene sea-level rise and its influence on southwest Florida coastal evolution: A transgressive/regressive stratigraphy. J Sediment Petrol. 59: 960-972. *Study on the accumulation of sediments in mangrove forests and mangrove islands.*

Robertson AI, Alongi DM. 1992. Tropical Mangrove Ecosystems. Vol. 41 Coastal and Estuarine Series. Washington, DC: American Geophysical Union. 329 p. *A review of sedimentology, hydrodynamics, floristics, forest structure, primary productivity, nutrient cycling, and food chains in mangrove forests.*

Saenger P. 2002. Mangrove Ecology, Silviculture, and Conservation. Dordrecht: Kluwer Academic Publishers. 360 p. *Contains chapters on the conservation and management of mangroves.*

Smith III TJ. 1992. Forest Structure. In: Robertson AI, Alongi DM. (eds.). Tropical Mangrove Ecosystems. Vol 41 Coastal and Estuarine Series. Washington, DC: American Geophysical Union. p. 101-136. *Summary of factors controlling distribution of mangroves.*

Smith III TJ, Anderson GH, Balentine K, Tiling G, Ward GA, Whelan KRT. 2009. Cumulative impacts of hurricanes on Florida mangrove ecosystems: Sediment deposition, storm surges and vegetation. Wetlands 29(1):24-34. *Some mangrove sites have recovered following catastrophic disturbance from hurricanes. However, other sites have been permanently converted to intertidal mudflats.*

Smith III TJ, Boto KG, Frusher SD, Giddins RL. 1991. Keystone species and mangrove forest dynamics: the influence of burrowing by crabs on soil nutrient status and forest productivity. Estuar Coast Shelf Sci. 33: 419–432. *The presence of burrowing crabs in mangrove substrate facilitates the production of mangrove detritus and affects soil nutrients.*

Strong AM, Bancroft GT. 1994. Patterns of deforestation and fragmentation of mangrove and deciduous seasonal forests in the upper Florida Keys. Bull Mar Sci. 54:795-804. *Review of periods of deforestation over the last 300 years in the Florida Keys, and a discussion of the probable effects deforestation had on the biodiversity of the Keys.*

Teh SY, DeAngelis DL, Sternberg LSL, Miralles-Wilhelm FR, Smith III TJ, Koh HL. 2008. A simulation model for projecting changes in salinity concentrations and species dominance in the coastal margin habitats of the Everglades. Ecol Model. 213: 245-256. *Development of a model to predict the shift of mangrove to tropical hardwood communities with varying salinities.*

Titus J, Richman C. 2001. Maps of lands vulnerable to sea-level rise: Modeled elevations along the U.S. Atlantic and Gulf Coasts. Climate Res. 18:205–228. *Development of coastal contour maps allows prediction of land loss with sea-level rise.*

Tomlinson PB. 1995. The Botany of Mangroves.

Mangrove Habitats

Cambridge: Cambridge University Press. 433 p. *Comprehensive summary of ecology, morphology, and physiology of mangrove communities, including a detailed description by plant family.*

Twilley RR. 1995. Properties of mangrove ecosystems and their relation to the energy signature of coastal environments. In: Hall CAS (ed.) Maximum Power: The Ideas and Applications of H.T. Odum. Denver, CO: University Press of Colorado. 43-62 p. *The concept of "emergy" applied to mangrove systems.*

Twilley RR, Chen RH, Hargis T. 1992. Carbon sinks in mangroves and their implications to carbon budget of tropical coastal ecosystems. Water Air Soil Poll. 64:265-288. *River-dominated coastal margins (including estuarine and shelf ecosystems) are important both to the regional enhancement of productivity and to the global flux of carbon in land-margin ecosystems. The tropical regions of the biosphere are the most biogeochemically active coastal regions and represent potentially important sinks of carbon in the biosphere.*

Twilley RR, Snedaker SC, Yanez-Arancibia A, Medina E. 1996. Biodiversity and ecosystem processes in tropical estuaries: Perspectives of mangrove ecosystems. In: Mooney HA, Cushman JH, Medina E, Sala OE, Schulze ED (eds.) Functional Roles of Biodiversity: A Global Perspective. Cichester, United Kingdon: John Wiley & Sons. p. 327-370. *Summary of ecosystem processes in mangrove forests.*

Walton TL. 2007. Projected sea-level rise in Florida. Ocean Eng. 34:1832-1840. *Future sea-level rise will lead to salt water intrusion, beach/dune recession, and many other coastal problems. Results show rate of sea-level rise for Florida is higher than past straight-line trend results.*

Wanless HR, Parkinson RW, Tedesco LP. 1994. Sea level control on stability of Everglades wetlands. In: Davis SM, Ogden JC (eds.) Everglades, the Ecosystem and Its Restoration. Boca Raton, FL: St Lucie Press. p. 199-222. *Current rate of sea-level rise is 6 to 10 times that of the past 3200 years and is triggering dramatic changes in coastal wetland communities, including accelerated erosion, landward encroachment of marine wetlands, and saltwater encroachment of surficial and groundwaters.*

Whelan KRT. 2005. The successional dynamics of lightning-intiated canopy gaps in the mangrove forests of Shark River, Everglades National Park, USA. Florida International University, Ph.D. Dissertation. 196 p. Available online at: http://sofia.er.usgs.gov/publications/thesis/lightning_gaps/Whelan-Thesis-HSH.pdf (Accessed 23 Feb 2011). *Lightning strikes are an important source of canopy gaps in the mangrove forest of Everglades National Park.*

Whelan KRT, Smith III TJ, Anderson GH, Ouellette ML. 2009. Hurricane Wilma's impact on overall soil elevation and zones within the soil profile in a mangrove forest. Wetlands 29:16-23. *An assessment of the impact of Hurricane Wilma (2005) on soil elevation at a mangrove forest location along the Shark River in Everglades National Park, Florida, USA.*

Whelan KRT, Smith III TJ, Cahoon DR, Lynch JC, Anderson GH. 2005. Groundwater control of mangrove surface elevation: Shrink and swell varies with soil depth. Estuaries 28: 833–843. *A determination of the relationship to groundwater changes and soil surface elevation change at a mangrove forest site along Shark River, Everglades National Park, Florida.*

Website references

Bargeron CT, Minteer CR, Evans CW, Moorhead DJ, Douce GK, Reardon RC. Technical Coordinators. 2008. Invasive Plants of the United States DVD-ROM: Identification, Biology and Control. University of Georgia Center for Invasive Species and Ecosystem Health and United States Department of Agriculture Forest Service. Forest Health Technology Enterprise Team. Morgantown, WV. FHTET-08-11. Available from: http://www.invasive.org/weedcd/species/3521.htm (Accessed 23 Feb 2011). *Images and discussion of invasive plants.*

Encora Coastal Portal. Potential Impacts of Sea Level Rise on Mangroves. Available from: http://www.coastalwiki.org/coastalwiki/Potential_Impacts_of_Sea_Level_Rise_on_Mangroves (Updated 18 Apr 2008; accessed 23 Feb 2011). *Summary of global distribution, ecological values, and responses of mangroves to changing sea level.*

Florida Coastal Everglades Long Term Ecological Research Programs. Available from: http://fcelter.fiu.edu/research/working_groups/?wg=11&p=FCEII (Accessed 23 Feb 2011). *Summary of research on four focus groups: Primary Productivity, Trophic Dynamics, Biogeochemical Cycling, and Organic Matter Dynamics in the coastal Everglades. Discussion of the potential impacts of increased freshwater flow on sawgrass and mangrove communities.*

Gilman EC. 2011. Coping with Climate Change: Escaping the Rising Sea. Technical Centre for Agriculture and Cooperation, African, Caribbean and Pacific Group of States and European Union. ICT Update, Issue 35, February 2007. Available from: http://ictupdate.cta.int/en/Feature-Articles/Escaping-the-rising-sea (Accessed 23 Feb 2011). *Predicting shoreline responses to rising sea level. American Samoa uses GIS and satellite images to monitor the retreat of mangroves and develop a long-term management plan.*

Quarto A. 2009. Mangrove Loss and Climate Change - A Global Perspective. World Rainforest Movement (Montevideo, Uruguay) Bulletin 132. Available from: http://www.wrm.org.uy/bulletin/132/Mangroves.html (Accessed 23 Feb 2011). *Less than 15 million hectares of mangroves remain on Earth, less than half the original area. There is need for a strong conservation ethic and enforcement of existing laws and regulations.*

Singh HS. 2003. Potential Impacts of Climate Change on Mangroves in India. Paper submitted to World Forestry Congress, 2003, Quebec City, Canada. Available from: http://www.fao.org/DOCREP/ARTICLE/WFC/XII/0894-B2.HTM (Accessed 23 Feb 2011). *Discussion and analysis of potential impacts of climate change on mangroves in India and suggestions for management of remaining mangrove resources.*

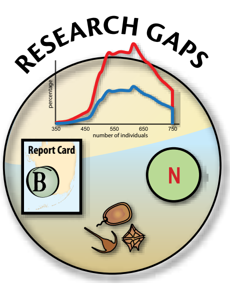
Smithsonian National Museum of Natural History: Ocean Portal. 2010. Worldwide mangrove distribution. Available from: http://ocean.si.edu/ocean-photos/mangroves-range (Accessed 15 Jul 2011). *Worldwide map showing mangrove distribution.*

United States Army Corps of Engineers and South Florida Water Management District. Comprehensive Everglades Restoration Plan. Available from: http://www.evergladesplan.org/index.aspx (Accessed 23 Feb 2011). *Facts and information about the Everglades and the Comprehensive Everglades Restoration Plan.*

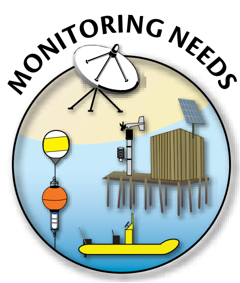
7. ANIMAL DIVERSITY

Animal Diversity
Chapter Recommendations

- Make **ecosystem restoration and biodiversity** a high priority of all management plans with an understanding that all habitats are linked.
- Consider the entire ecosystem when locating and designing **Marine Protected Areas**. Multiple habitats may have to be included for conservation of species that use different habitats throughout their life histories.
- Control **overfishing of major predators**, as they are the "lions" of the sea. It is very inefficient and ecologically destructive to harvest apex predators for food.
- Promote **aquaculture** as an alternative to wild harvest for food and to provide organisms for ecosystem restoration efforts.
- Educate the public on **invasive exotic species** to control their introduction and detrimental impacts to the ecosystem.
- Promote ecotourism and familiarize the public with the grandeur and importance of **megafauna and biological diversity.**



- Quantify the impacts of the **loss of major predators** on ecosystem structure and function.
- Quantify the impacts of **increased algal growth** on ecosystem structure and function.
- Develop methods to facilitate **ecosystem recovery**.
- Develop methods to control impacts of **invasive exotic species and harmful algal blooms**.
- Investigate **aquaculture alternatives** to maximize yields while protecting natural resources.
- Quantify effects of protection on reproductive potential and **"spillover" effects of Marine Protected Areas**.



- Quantify effects of **Marine Protected Areas** on ecosystem recovery, including an analysis of their impact on population size of a wide range of organisms with different ecological requirements.
- Quantify ecosystem changes caused by **invasive exotic species and harmful algal blooms**.
- Conduct long-term monitoring of water quality to assess the **"pulse" of the ecosystem** and assess changes required to improve conditions.
- Identify and monitor **sentinel species** of ecological change.

Chapter title page: School of permit. J.S. Ault, UM/RSMAS

Introduction

This chapter is an overview of some of the large, charismatic animals that occur in the south Florida marine ecosystem, including some with significant local economic importance. The animals discussed in this chapter are those normally recognized as prominent and distinctive to south Florida. Several are "keystone species;" that is, species that have a major influence on the structure and function of the ecosystem. For example, the community structure of reefs is very different without the presence of large predators such as goliath groupers and sharks that were historically abundant. Conservation of populations of keystone species is vital to the restoration of healthy ecosystem structure and function.


M. O'Malley - sharksavers.org

Tiger sharks were more common in south Florida and their population has been negatively impacted by overfishing. Reef fish community structure has undoubtedly changed with the reduction of shark populations.

Biodiversity is ecologically important

The animals discussed in this chapter represent a small fraction of the amazing diversity of animal life in the region. The word "biodiversity" is a contracted form of "biological diversity" and was coined by E.O. Wilson to convey that the preservation of the Earth and its ecosystems relies on the broad genetic diversity of all organisms on Earth.[1] High biodiversity is often used as a measure of the "health" of a biological system.[2,3] The biodiversity found on Earth today consists of many millions of distinct biological species, each one of which is a biological resource that is important to the structure and function of the entire biosphere.

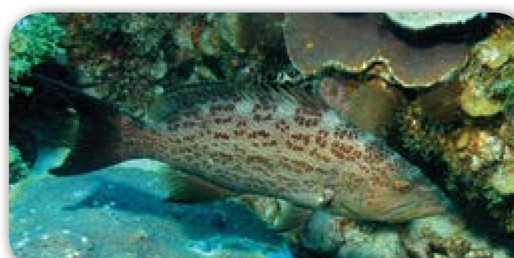
Paul Ehrlich proposed the following analogy regarding the importance of maintaining biodiversity. Imagine the habitable space on Earth and all of the organisms as an airplane in flight, with each organism a rivet that holds the airplane together. When a species is lost (i.e., becomes extinct) the airplane loses a rivet. The plane may continue to fly with the loss of a rivet or two, but if it loses too many rivets, the structure fails and the plane crashes. Some rivets are more important than others. For example, some species, called "foundation species," build habitats that are required for other species to survive (e.g., corals, oysters, mangroves, seagrasses). Losing just one important foundation species can cause the plane to crash just as easily as losing several others. Unfortunately, scientists do not know as much about the interaction of organisms as they do about airplanes, and do not know when losing one more species is too many, or when losing any particular species will result in a crash.[3]

Biodiversity is not evenly distributed on Earth, but is consistently richest in tropical climates, including coral reefs and tropical rain forests, and lowest in polar regions.[3,4] Biogeographic provinces are geographic regions that contain distinctive climatic regimes and habitats and distinctive faunal assemblages. South Florida exists near the confluence of the Carolinean (about Cape Hatteras to Cape Kennedy), Louisianan (about Cedar Key to Mexico), and the West Indian Biogeographic Provinces and species from all three provinces live there. Thus, the climate, geography, and diversity of habitat types (i.e., mangrove forests, seagrass meadows, hardbottoms, sandy areas, patch reefs, barrier reefs, and open ocean) in south Florida contribute to an amazing biodiversity of plant and animal life within its waters. For example, over 500 species of fishes are found in south Florida marine environments.[5]

Maintaining biodiversity helps provide for basic human needs, such as food, shelter, and medicine. Plants and animals that comprise this biodiversity maintain oxygen in the air, enrich the soils, purify the water, protect against flood and storm damage, and regulate climate. Biodiversity also has recreational, cultural, spiritual, and aesthetic values.[1,4] Rapid environmental changes typically cause major losses in biodiversity, including extinctions. Of all species of plants and animals that have ever existed on Earth, 99.9% are now extinct. Since life on Earth began, there have been five major mass extinction events that resulted in large and sudden drops in species biodiversity. The Phanerozoic Eon (the past 540 million years) marked a rapid growth in biodiversity during the Cambrian "explosion", a period during which nearly every phylum of multicelluar organisms first appeared on Earth. The next 400 million years was distinguished by periodic, massive losses of biodiversity through mass extinction events. The most recent, the Cretaceous-Tertiary extinction event, occurred 65 million years ago and included the loss of the dinosaurs.[1]

Extinction is a natural process, but has never before occurred at such a fast rate as today. There is concern that the period since the emergence of humans is part of a mass reduction in biodiversity called the "Holocene extinction", caused primarily by the impact humans have on the environment. In addition, human practices have caused a loss of genetic biodiversity through selective harvesting and breeding. It is thought that human activities have raised the rate of extinction to 1000 times its usual rate.[6] The main causes of loss of biodiversity today are loss of habitat, introduction of invasive species, growth of the human population, pollution, and overconsumption of natural resources.[1]

Organisms do not have to disappear entirely from the planet to cause detrimental impacts to the structure and function of an ecosystem. "Ecological extinction" describes the reduction of a population to a size that can no longer provide important ecological functions to the remainder of the ecosystem.[7] For example, the long-spined sea urchin (*Diadema antillarum*) succumbed to an unknown disease in the early 1980s. Although it still occurs in small numbers throughout the region, it is ecologically extinct from much of the Caribbean region, including south Florida. As a result there is an increased growth and abundance of macroalgae that the sea urchin normally would have grazed.[8] Increased abundance of macroalgae has inhibited coral recruitment on many reefs. Already, an estimated two of every three bird species are in decline worldwide; one in every eight plant species is endangered or threatened; and one quarter of mammal species, one quarter of amphibians, and one fifth of reptiles are endangered or vulnerable.[6,9,10]


J. Luo - UM/RSMAS

Scamp is a heavily overfished grouper species.

Factors influencing biodiversity in south Florida

The following discussion is not an inclusive list of all factors that have a detrimental impact on biodiversity in south Florida, but rather an introduction to three of the most visible and potentially most subjective to management actions.

Overfishing

Overfishing, destructive fishing techniques, and other human activities have severely jeopardized the health of many worldwide fish stocks and associated marine species and habitats. The Food and Agriculture Organization of the United Nations estimated that nearly two thirds of ocean fisheries are exploited or beyond capacity.[6] The relevance of biodiversity to human food harvesting and health is becoming a major international issue as increasingly more scientific evidence is gathered on the implications of biodiversity loss on global health. This has led to the declaration of the year 2010 as the International Year of Biodiversity by the United Nations, in recognition of the importance of maintaining biodiversity to ecosystem health, human health, and quality of life.[10]

Florida Keys Public Libraries

Historical overfishing (ca. 1980s) contributed to the collapse of goliath grouper populations.

Humankind has caused ecological extinctions both on land and in the ocean. On land, humans killed off many giant mammals and destroyed ancient forests, but replaced them with a new suite of farmed species. In the ocean, humans systematically harvested the large animals (e.g., tuna, swordfish, goliath grouper, sea turtles, manatees) and have not replaced them with other species.[11] Thus, the south Florida marine ecosystem is a very different place than it was before the arrival of European settlers, and overfishing was a primary driver of ecosystem collapse.

Dr. Jeremy Jackson convened a team of leading international marine scientists that examined paleoecological, archeological, and historical data on marine ecosystems worldwide. The team discovered that the ancient seas teemed with large animals, including whales, seals, large sharks, large fish, and oysters and other shellfish resources so vast that they posed hazards to navigation. The many tens of millions of sea turtles that existed in the Caribbean before Columbus arrived easily exceeded the abundance and biomass of large mammals in East Africa. Overfishing triggered changes in ecosystem structure and function as early as the late aboriginal and early colonial stages and the ensuing "grinding down" of marine food webs has been responsible for many of the problems that humankind faces in marine waters today.[12] Data show that time lags of decades to centuries occurred between the onset of overfishing and consequent changes in ecological communities, because unfished species of similar trophic level assumed the ecological roles of overfished species until they too were overfished or died of epidemic diseases. Today, scientists have concluded that all we do is micromanage remnants of once vast populations. Removal of key predators, such as large sharks (i.e., a top-down control of ecosystem structure), and the loss of entire layers of the food chain (e.g., all large groupers) set off sequences of events that now culminate in symptoms of ecosystem "meltdown", including toxic algal blooms, dead zones, jellyfish abundances, disease outbreaks, and other symptoms of instability.[12]

In south Florida, overfishing of large fish contributed to overgrowth of algae on coral reefs that has smothered the reefs and has jeopardized the approximate 3 million species that the coral reefs harbor. Dr. Jackson opines that the recent die-off of turtle grass beds in Florida Bay may be attributed in part to the ecological extinction of green sea turtles. Overkill of the green sea turtle and other large

Monroe County Public Library, courtesy of L. McClenachan

Green turtles were overharvested for their meat in south Florida.

seagrass grazers such as manatees, may have contributed to outbreaks of disease and die-offs in seagrasses.[12]

Invasive exotic species

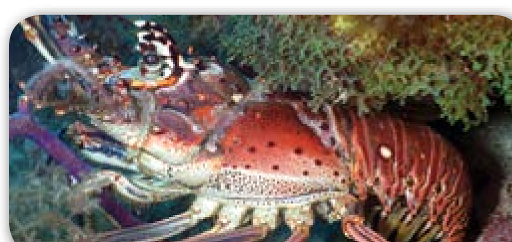
A relatively recent threat to south Florida marine waters is the invasion of exotic species of plants and animals. Since 1999, 16 nonnative marine fish species have been documented in the southeastern Atlantic.[13] Invasive exotic species are not constrained by natural controls that exist in their native habitats, such as predators and diseases. Their rapid growth and spread has the potential to alter what remains of natural areas, resulting in economic and environmental harm.[14] The lionfish, native to the Indo-Pacific region, was first reported in Biscayne Bay in 1992 and has spread throughout the western Atlantic Ocean.[15] Invasive species can completely alter ecosystems. For example, researchers in the Bahamas found that a single lionfish transplanted onto a small patch reef reduced recruitment of native fishes by nearly 80% over a 5-week period.[16]

Harmful algal blooms

Algal blooms can also cause a loss of ecosystem biodiversity. In 1990, deep reefs off Palm Beach and Broward Counties experienced an unprecedented succession of macroalgal blooms. A bloom of the green algae *Codium isthmocladum* resulted in an accumulation of up to 2 meters (6.5 feet) of algae over reef surfaces.[17] This resulted in a mass emigration of reef fishes from impacted areas and die-off of benthic organisms, including hard corals, soft corals, and sponges due to smothering and anoxic (no oxygen) conditions. The bloom was determined to result from land-based nutrient pollution, particularly nitrogen from sewage.[18] There are several other recent examples of the impacts of harmful algal blooms on the south Florida marine ecosystem. Since the seagrass die-off event, Florida Bay has periodically experienced blue-green algae phytoplankton blooms (*Synechococcus* sp.) that have changed the structure of fisheries[19] and destroyed juvenile lobster habitat.[20] The 2002 blackwater event caused vast damage to benthic communities on the Southwest Florida Shelf. Periodic blooms of red tide (*Karenia brevis*) are known to cause massive fish kills and manatee deaths.

The Caribbean spiny lobster is of particular importance to the economy of south Florida

A portion of this chapter is devoted to a description of the life history, threats, and conservation measures of the Caribbean spiny lobster, also known as the Florida spiny lobster, as a detailed example of the need to understand and manage a keystone species. Over the long term, the spiny lobster fishery ranks third in Florida behind shrimp and stone crab claws. The average commercial landings of spiny lobster from 2006 – 2010 was approximately 1.8 million kilograms (4 million pounds) with an annual average value of $25 million. Most of the annual harvest comes from Monroe, Miami-Dade, and Broward Counties.[23,24]


J. Luo - UM/RSMAS

Knowledge of the life history, habitat requirements, threats to the population, sustainable yield, and potential conservation measures must be understood to effectively manage the Caribbean spiny lobster.

Spiny lobsters rely on many habitats in the south Florida marine ecosystem to complete their life cycle. Adult spiny lobsters are found in crevices of coral reefs and hardbottom habitats. Their main reproductive period is March – August and lobster eggs hatch into larvae that can be carried hundreds of miles by ocean currents. A portion of the lobster population of south Florida probably results from larvae spawned in the Caribbean Sea and transported to the region by currents.[25] Postlarvae settle in shallow water algae beds and become juvenile lobsters. After a period of solitary growth, juveniles congregate around daytime protective habitats, such as large sponges. As they mature, they migrate from nursery areas to offshore reefs.[26] Although they can grow as large as 7 kg (15 lbs), because of the intense fishing pressure, the average lobster caught in south Florida is just over the minimum carapace length of 7.6 centimeters (3 inches) and weighs about 0.5 kg (1 lb). It takes about 2 years for a lobster to grow to minimum legal size.[27]

The quality of juvenile lobster habitat has declined in Florida. Juveniles prefer to live under loggerhead and vase sponges. In recent years, many of those sponges have died due to phytoplankton blooms. Understanding and managing water quality factors that influence nearshore phytoplankton growth is critical to the health of the lobster population. Recently, juvenile lobsters were found to be susceptible to a lethal viral disease that was not observed in the past. Understanding conditions that cause the outbreak and spread of this disease is critical to the future of spiny lobsters in south Florida.[28]

There are several things that can be done to help conserve lobsters, such as releasing undersized lobsters and egg-bearing females unharmed. Careful operation of boats and proper dive techniques are also essential to preserve lobster habitats. Establishment of carefully located no-take zones can result in establishment of populations of large individuals that may result in increased recruitment.

Personal choices and actions can influence animal diversity

Scientists conclude that responding to current events on a case-by-case basis cannot solve the global ocean problems because impacts of human disturbance are synergistic and have deep historical roots. Ecological extinctions that have already occurred make ecosystems more vulnerable to other natural and human disturbances, such as nutrient loading, eutrophication, anoxia, disease, and climate change.[12] Many species described in this chapter and elsewhere in this book are overfished, endangered, threatened, or scarce. Many populations are comprised of individuals that are smaller in overall size than they were historically because large individuals are routinely removed from the population by overfishing. With a few exceptions, however, such as the extinct Caribbean monk seal, most species that are ecologically extinct probably still survive in sufficient numbers for successful restoration with proper management. This stands in contrast with many terrestrial ecosystems, where many or most large animals are already extinct.[12]

Resource managers must target ecosystem restoration as a high priority and fund research on developing dependable methods of restoring and maintaining ecosystem structure and function.[29] Stemming corals lost to disease must start with basic research on the etiology of disease-causing organisms and conditions. Building up overfished stocks may require setting aside large areas as no-take marine reserves, in conjunction with implementing strict fishery regulations. Controlling invasions of exotic species requires an understanding of their biology and natural controls. All efforts require an appreciation and understanding of the entire marine ecosystem so that gains in one area are not to the detriment of other areas. And finally, all efforts require education of the public to gain their appreciation of the problem and their cooperation and support in working toward a resolution.[10,12]

The queen conch is the symbol of the Florida Keys

Robert A. Glazer and Gabriel A. Delgado

The queen conch is a large marine snail that was once so ubiquitous in the Florida Keys that residents of the island chain adopted it as their namesake: The Conch Republic. Hotels, restaurants, shops, and even the Key West High School mascot are named after the queen conch. Locals born in the Florida Keys are bestowed the honorary title "Conch."

Unfortunately, years of overfishing, habitat change, and declining water quality have left the queen conch much less common than they once were. The steady decline of the population resulted in the closure of the commercial fishery for conch in 1975. In 1986, recreational harvest was prohibited. Until about 2000, there was little sign of recovery. Then, the population started to rebound. However, after peaking in 2003, the conch population has declined again.

Florida is not the only place where conch populations are declining. After spiny lobster, conch represents the most

Wikimedia

The residents of the Florida Keys nicknamed the island chain "The Conch Republic" and created their own flag.

Monroe County Public Library

Historical photo of queen conch shells hanging from Southernmost Point, Key West.

important single-species catch in the Caribbean region. The 2003 annual catch values were estimated at $60 million U.S. dollars. The desirable meat and the ease of capture have resulted in a long-occurring, regionwide decline in population numbers throughout its range.

In 1991, the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES) listed queen conch, thereby requiring all signatory nations that export conch to have a management plan in place that will ensure the survival of the species. Almost all countries in the region are signatories of CITES. Queen conch was the first fishery species listed with CITES and it marked a monumental moment in the management of the international trade in marine fishery species.

In Florida, queen conch are found from the Dry Tortugas to as far north as St. Lucie Inlet, Martin County. They are most common in the Florida Keys, where they are found in two isolated zones. The first zone is nearshore, immediately adjacent to the island chain. This zone once comprised a large subset of the population, but in the last several years the abundance of nearshore conch has declined precipitously. The few conch that remain nearshore are found primarily in hardbottom communities and less commonly in seagrass meadows. Shells of conch in the nearshore are usually very colorful, with deep iridescent orange and pink colors seen on their insides. The coloration results from their primary diet of red algae. One aspect of the biology of nearshore conch is troublesome: these conch never reproduce because their gonads never fully develop. Conch are much more common offshore and serve as the reproductive population for the Florida Keys. They typically inhabit the shallow back reef zone and dense aggregations can be found in rubble, coarse sand, and seagrass habitats.

W.L. Kruczynski - EPA

Conchs have been harvested for food by coastal populations and piles of empty shells are found throughout its geographic range.

Wikimedia

Since 1991, the export of queen conch is protected by the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES).

Animal Diversity

The queen conch has a complex life cycle

Robert A. Glazer and Gabriel A. Delgado

Only conch found offshore in the Florida Keys are reproductively active. In the summer, male and female conch come together to mate when they are approximately 3 – 4 years old. After mating, females lay an egg mass that looks like a French croissant in course sand. Within the egg mass are tiny spaghetti-like strands that contain the eggs, and each egg mass may contain up to 400,000 eggs. Fertilized eggs develop into embryos within the egg membrane. Approximately 4 days after fertilization, eggs hatch into microscopic, free-swimming larvae that are about the size of the period at the end of this sentence. Conch larvae can control their position in the water column and are dispersed by currents. Larvae feed mostly on microalgae (i.e., phytoplankton). After about 3 weeks, they settle onto the seafloor and burrow into sandy bottom sediments.

A year after they settle, juvenile conch emerge and live on the surface of the sea bottom. Only about one out of eight million eggs will survive to reproduce because they are preyed upon at varying stages in their life cycle by a number of animals. Among those that eat juvenile conch are Caribbean spiny lobsters, crabs, tulip shells, porcupine fish, horse conch, nurse sharks, and loggerhead turtles.

Florida conch are local

Conch larvae can float with currents for as long as 4 weeks. So, conch hatched as far as Belize could easily travel as larvae to south Florida. It is possible that larval influx from upstream sources may have occurred in the past, but is currently greatly diminished, probably as a result of Caribbean-wide overfishing of queen conch. Consequently, there appears to have been a shift in the origin of recruits to the Florida Keys from a mixture of upstream and locally produced larvae to a greater reliance on local sources. Thus, it is important that management of conch focus on conserving and enhancing local spawning populations.

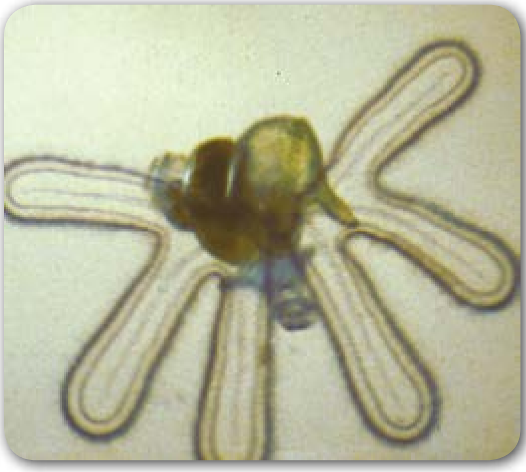
FWC

A female queen conch laying an egg mass (red arrow).

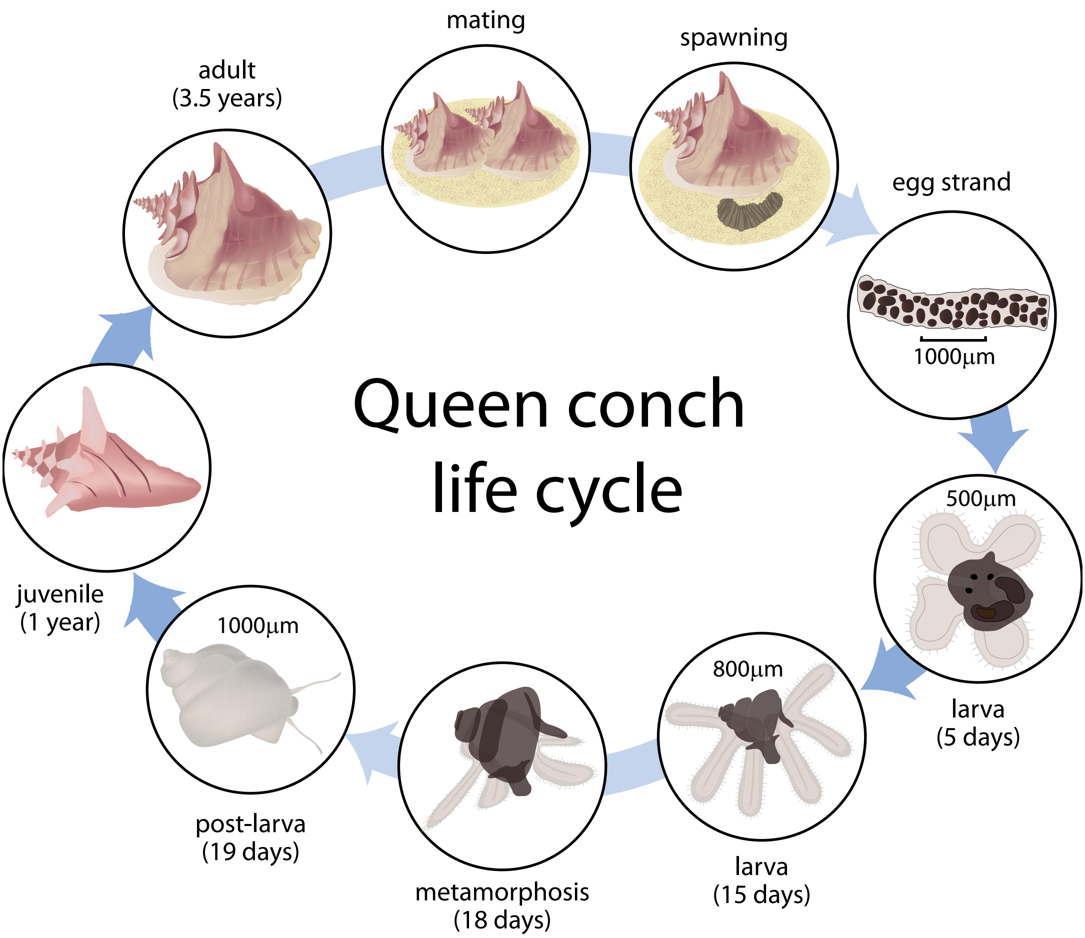
FWC

Queen conch was once common in Florida, but current populations are very low.

Conch embryos in a strand of egg mass. At this stage the shell is already formed. The eyes are two dots.



A 14-day old larva. The long lobes help keep it suspended in the water column and direct food toward the mouth.



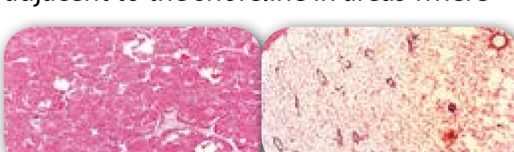
Queen conch have a complex life cycle (µm = micron [1/1000th of a millimeter]).

Water quality impacts queen conch populations

Robert Glazer and Gabriel Delgado

Queen conch is a large marine snail that symbolizes the Florida Keys . They were once common enough in Florida to support a commercial and recreational fishery. However, the population has declined substantially and even though harvest has been prohibited for the past 20 years, population levels are still very low. The Florida Fish and Wildlife Conservation Commission (FWC) has been examining ways to restore the populations of queen conch. Evidence collected over the last decade indicates that declining water quality may be partly responsible for the lack of recovery of the queen conch population. In the 1990s, the FWC constructed a hatchery in the Florida Keys and grew conch from locally collected eggs. It was observed that larvae in the hatchery survived best when the seawater medium was treated with ozone and activated carbon to remove contaminants and dissolved organic materials. Compared with other conch hatcheries in the Caribbean region, larvae grown in untreated seawater in the Florida Keys required twice as long to grow to settlement size and needed to be reduced in density in culture tanks by 20 times. Something was clearly amiss!

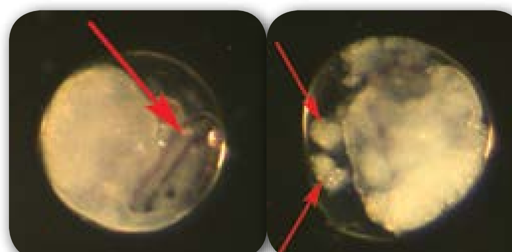
At the same time, FWC scientists made a startling discovery: a significant number of adult populations of queen conch in the Florida Keys no longer reproduced because their gonads never fully developed. The conch that did not reproduce were found immediately adjacent to the shoreline in areas where conch had historically reproduced.



N. Brown-Peterson - USM

Microscopic sections of ovaries from normal offshore female conch (left) and nonreproductive nearshore conch (right). Dark red cells are responsible for egg production and are missing in nearshore conch.

However, conch found further offshore, in close proximity to the bank reef, had normal gonads and reproduced successfully. FWC conducted a translocation experiment in which they moved conch from offshore to nearshore and vise versa. They discovered that conch that were moved offshore developed normal gonads and began reproducing in as little as 3 months after relocation. They also observed that the gonads of the conch that were moved nearshore deteriorated and reproduction ceased.



FWC

Four-day-old conch embryos in normal seawater (left) and exposed to Naled (right). Arrow on left points to eye spots. Arrows on right point to abnormal cells.

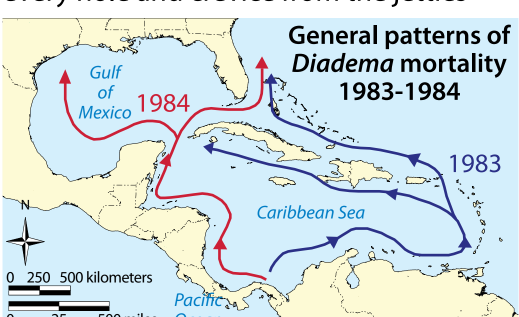
Several studies have examined the effects of a wide suite of contaminants on all stages of conch development, including embryonic, larval, and adult stages. Conch eggs were exposed to two mosquito control pesticides, Permethrin and Naled, used in the Florida Keys at concentrations seen in the field after spraying. There were no lethal effects on conch larvae, but there were chronic effects on conch embryos, including development of abnormal cells. A recently completed study examined the effects of heavy metals, pharmaceuticals, industrial and agricultural chemicals, and nearshore water temperature on reproductive success. It was concluded that zinc and/or copper may be partially responsible for lack of reproductive success in nearshore conch.

The long-spined sea urchin population was decimated by a Caribbean-wide plague

Martin A. Moe, Jr.

The long-spined sea urchin (*Diadema antillarum*) grazes on algae growing on reefs. The urchins are instrumental in maintaining ecological balance between coral and macroalgae and "conditioning" the rock substrates for growth of crustose coralline algae, which is critically important for settlement of corals and other reef organisms. In 1983, near the beginning of the precipitous decline of western Atlantic coral reefs, a great plague occurred that directly affected only one organism, the keystone herbivore of coral reefs, the long-spined sea urchin. This loss resulted in a shift in many reefs from a coral-dominated community to one dominated by macroalgae.

The epidemic began off the Panama coast in January 1983 and coincided with record elevated sea surface temperature in November – December 1982 in Panama. The plague, caused by a yet unknown pathogen, spread rapidly and within a year *Diadema* populations from the Caribbean to the Florida Keys and the Bahamas northward to Bermuda were decimated. It is estimated that between 96% – 99% of the billions of *Diadema* in this vast 3.5 million km^2 (1.35 million mi^2) oceanic habitat died within 12 – 13 months. The vast populations of long-spined sea urchins that inhabited almost every hole and crevice from the jetties along the shore out to the offshore bank reefs were gone within a few months. They had been present in numbers up to $20/m^2$ in some rugged areas of the Caribbean and averaged about 4 – $5/m^2$ over most Florida reefs. The loss of the *Diadema* was the most extensive mass mortality ever reported of any marine animal, and the ubiquitous long-spined sea urchin was suddenly very near extinction in the western Atlantic.



Adapted from Lessios (1988)

General patterns of the spread of *Diadema* mortality from 1983 (blue line) – 1984 (red line). The plague spread rapidly throughout the Caribbean Basin causing up to 99% mortality.

The ecological impact of the loss of the *Diadema* was soon apparent. In Jamaica, algae cover on the shallow reefs increased from 1% to as high as 95% within 2 years, and at St. Croix, algal biomass increased by 27% within 5 days after the *Diadema* mortality and then algal biomass increased by 300% – 400% above the pre-*Diadema* mortality levels. Similar increases in algal biomass following the mortality were observed throughout the Caribbean and tropical western Atlantic reefs. Thick growths of macroalgae and pads of turf algae trap sediments and compete with corals for substrate and sunlight. This extensive algal cover retards and even kills existing corals and greatly reduces settlement and growth of juvenile corals.

It was expected that *Diadema* would quickly return to the reefs given their immense reproductive potential, as females can release millions of eggs at each spawning. However, almost 30 years later, only a relatively few, widely scattered individuals and some weak population concentrations are present on Florida and Bahamian reefs. Predation on juveniles and adults, lack of spawning success from widely scattered adults, and paucity of proper substrates for larval settlement have prevented establishment of ecologically functional populations. If large populations do not soon return to Florida waters, there may be little left of the glorious coral reefs of the Florida Keys and the southeast coast.

Long-spined sea urchin "farming" is one component of reef restoration

Martin A. Moe, Jr.

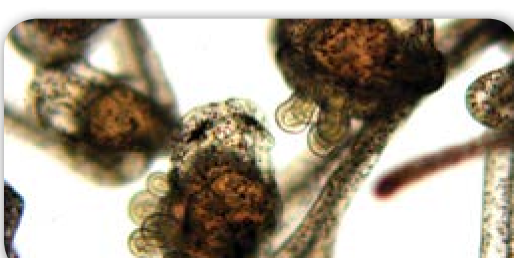
No one knows if or when *Diadema* populations will naturally rebound to pre-die-off numbers. Because *Diadema* are essential to the ecological health of coral reefs, research has been performed on laboratory rearing techniques (i.e., aquaculture) and the effectiveness of transplanting laboratory-reared urchins on coral reefs. Large-scale hatchery production of juvenile *Diadema* has just recently been accomplished and large numbers of laboratory-reared juvenile *Diadema* will soon be available. Assuming that the cause of the regionwide decline has passed, having juvenile urchins available in large numbers will open many avenues toward reestablishing healthy population densities of adult *Diadema* on Florida reefs.

Diadema eggs are fertilized in open water and the larvae are planktonic for 30 – 60 days. At settlement, the juvenile urchin metamorphoses within 1 hour from a rudiment that grows out of the larvae during the last week of larval life. One of the many challenges in laboratory rearing is maintaining and feeding the planktonic larvae in suspension by simulating ocean currents.

A few laboratory-reared juveniles have been transplanted to reef study sites and have been monitored for survival and growth. Many animals, including fish, spotted lobsters, crabs, and octopus eat juvenile urchins, so transplants must be protected from predation until they can hide in nooks and crannies of the coral reef.

M.A. Moe Jr. - MML

Laboratory-reared juvenile urchins are placed on reefs at about the size of, or a little larger than, this wild juvenile.



M.A. Moe Jr. - MML

Laboratory-reared planktonic larvae of *Diadema antillarum*. Maintaining larvae in suspension is one of the many challenges in culturing this organism. Large-scale larvae aquaculture of *Diadema* through metamorphosis and into the early juvenile stage has recently been accomplished.

Scientists are working on the establishment of natural coral reef "laboratories" designed and managed to restore degraded reef sites. Professional and volunteer reef caretakers service small, carefully selected reef areas. There they perform essential restorative functions, such as hand clearing excessive macroalgal growth, placement and maintenance of hatchery-produced coral fragments and juvenile corals, and establishment and maintenance of a functional population of hatchery-reared *Diadema* urchins. Keeping written and photographic records of the coral reef laboratory is essential to document success. Restoration of degraded coral reef areas is possible, but will take time, effort, and commitment to achieve success.

Biodiversity of reef fishes is important to the ecosystem and economy of the Florida Keys

James A. Bohnsack

Biogeography

The Florida Keys are known for their diverse marine habitats and productive fishery resources. The reef fish community of the Keys is characterized by high numbers of species (i.e., biodiversity) and high productivity, which is due in part to the geographic location of the islands. The Florida Keys are located at the geographical boundary among three large marine ecosystems: the Caribbean, Gulf of Mexico, and the subtropical Western Atlantic Ocean, and the Keys share fish species from all three. The healthy and diverse fish community supports commercial, recreational, and aquarium fisheries, and is an attractive focus for snorkeling and SCUBA diving, educational and tourism activities.

The Florida Keys are located at the boundary between the Caribbean, Gulf of Mexico, and tropical Western Atlantic ecosystems and share species from all three regions.

There are 442 fish species reported from the Dry Tortugas at the western-most Florida Keys Reef Tract, and about 300 of those species are closely associated with coral reefs. A total of 517 fish species occur at the Alligator Reef region in the Upper Florida Keys, of which 389 were considered reef-associated; the remaining 128 species are offshore pelagic forms, deeper water bottom fishes, or stragglers from inshore waters. Among the 389 reef-associated species, 253 were obligate reef species that required coral reef habitat, while the other 136 species were considered "secondary" reef species that opportunistically use coral reefs, but are equally or more characteristic of other nonreef habitats. Examples of secondary reef species include the great barracuda, snook, jacks, and sharks, all of which occur on coral reefs as older juveniles or adults, but also use a wide variety of other coastal and offshore habitats.


J. Luo - UM/RSMAS

Coral reefs are characterized by a diverse fish community.

Life history

Most reef fish have a two-part life cycle consisting of a pelagic (i.e., open ocean) and a demersal (i.e., bottom-dwelling) stage. Typically, fish begin their pelagic existence as eggs released and fertilized in the water column. Some species, such as damselfish, attach their eggs to the bottom in nests, but when hatched the larvae begin a pelagic existence. Larvae are potentially dispersed over wide areas by ocean currents. Pelagic larvae live about a month in the water column before settling to the bottom as juveniles. After settlement juvenile fishes spend the rest of their lives in a demersal stage which is closely associated with bottom habitats.

Mortality is extremely high in the pelagic stage. Even though adult reef fish can spawn hundreds of thousands or millions of eggs, very few, perhaps tens or a few hundred, actually survive to become juveniles. Many eggs are never fertilized, or are consumed by reef fish and planktonic predators, such as jellyfish and arrow worms. Others may starve because of unfavorable oceanographic conditions or may be swept away into unsuitable adult habitat by currents, storms, or other variable oceanographic and weather events. After settlement, mortality is much lower in the demersal stage than in the pelagic stage, although only a few individuals may actually survive to adulthood. As adults, reef fishes are characterized by low natural mortality and high survival rates.

Many reef fish species complete their juvenile and adult life cycle entirely on coral reefs, including angelfish, butterflyfish, cardinalfish, blennys, damselfish, gobies, morays, parrotfish, surgeonfish, and wrasses. Other species are found on coral reefs only as adults, including most of the economically important reef fishes caught for sport and food, such as snapper (Lutjanidae), grouper (Serranidae), grunt (Haemulidae), porgy (Sparidae), and the hogfish (*Lachnolaimus maximus*, a wrasse). These fish change their habitat requirements as they grow: their larvae settle into nursery habitats, such as seagrass, mangroves, and algal flats in Florida Bay and other shallow coastal areas, and as they grow, they eventually migrate to offshore coral reefs as older juveniles or adults.

The pelagic stage is the dispersal phase for most reef fishes. Dispersal occurs when ocean currents transport offspring over long distances. Reef fish can potentially reach Florida from Cuba, the Bahamas, and the Meso-American reef along Belize and Mexico, as well as from the Gulf of Mexico and U.S. southeastern Atlantic. Important currents that influence the Florida Keys include the Loop Current in the Gulf of Mexico along the west Florida shelf, the easterly Florida Current in the Florida Straits to the south and the Gulf Stream and its countercurrents along the east coast. Despite a potential for long distance dispersal, there is also evidence that many, if not most, larvae produced in the Florida Keys remain within the Florida Keys ecosystem and can even be returned to natal reef areas. Large gyres and eddies, such as the Portales Gyre in the Lower Florida Keys, can last about a month, while the Tortugas Gyre off southwestern Florida can last about 2 months, allowing sufficient time to potentially return larvae to the nursery habitats in the Keys.


M. Freeley - FWRI

Mutton snapper spawning aggregation in the Tortugas coincides with gyre formation and optimizes recruitment of young to the area.

Adult reef fishes are highly residential with some species spending their entire demersal lives at one reef or location. Some species may make brief annual spawning migrations as mature adults, but then return to their home reef. The annual spring spawning migrations of mutton snapper (*Lutjanus analis*) to the Southwest Florida Shelf occur at times that coincide with optimum gyre formation. This spawning site is located upstream from the prevailing currents and is ideal for ensuring that larvae are retained in Florida. This spawning migration may reflect behavior developed during past ice ages when fish made annual migrations to warmer environments.

Stressors and threats

Florida Keys reef fish face threats from natural events and human activities.

Natural events that damage reef fish populations include mortality from harmful algal blooms, extreme cold or hot weather, tropical storms and hurricanes, and disease epidemics. Detrimental human activities include overfishing and destruction or degradation of reef or nursery habitats. Sources of stress include excessive turbidity; sedimentation and water delivery modifications; nutrients from terrestrial sources; direct damage to habitat by vessel groundings; habitat loss from coastal development; and accidental or deliberate introductions of invasive species. Long–term threats associated with climate change, such as sea-level rise and ocean acidification, are major concerns, although their impacts are difficult to quantify or predict at the present time.

Coral reef fish are characterized by high longevity, large body size, slow growth, delayed reproduction, and low adult natural mortality. These adaptations for successful coral reef survival ultimately make reef fish vulnerable to overfishing. Most fishing is size selective in that the largest and oldest individuals are targeted and removed, which results in high adult mortality. Reef fish also are vulnerable to overfishing because of their aggressive feeding behavior, lack of wariness of fishing gear, the limited amount of reef habitat, and spawning migrations to specific sites at predictable times. Some species, such as groupers, have another restriction in that they are all born as females and the largest females change sex to become males. Fishing depletes the larger and older individuals which can result in sperm limitation if too few males survive to fertilize eggs. This life history peculiarity also reduces the number and average size of females, which results in considerably fewer eggs produced.

Reef fishery management

Excessive fishing pressure to reef fish populations is a major threat even though, in theory, fishing should be easy to regulate. Traditional fishery regulations do two things: either limit total fishing effort to control fishing mortality, or control the size and age of capture. Tools to achieve these goals include restricting allowable fishing gears, protecting critical habitats, and establishing fishing seasons, bag limits, landings quotas, minimum size limits, and areas permanently closed to fishing. No-take marine reserves, where all fishing and other extraction methods are permanently prohibited, were established in the Florida Keys in 1997, 2001, and 2007. Monitoring has demonstrated beneficial effects of no-take marine reserves for reef fish populations in these protected areas and suggests that reserves can benefit fisheries by reducing the chances of overfishing and increasing the replenishment of reef fish populations. Marine reserves are most likely to be effective when combined with other traditional management tools. Perhaps the biggest remaining obstacle for fishery management is reconciling the fact that coral reef ecosystems have a finite and limited capacity to support fisheries in the face of growing human populations and their increasing demands for reef resources.

J. Fiengold - NOAA Photo Library

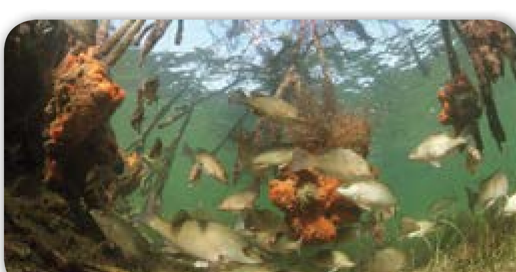
Reef fish management includes both protecting critical reef fish habitats and reducing fishing pressures.

Gray snapper use oceanic, seagrass, mangrove, and coral reef habitats as they grow

Joseph E. Serafy

A conspicuous component of south Florida fish communities, the gray snapper (*Lutjanus griseus*) is found from Massachusetts to Brazil and throughout the Gulf of Mexico and Caribbean Sea. Maximum reported age, length and weight is 24 years, 89 centimeters (35 inches) and 20 kilograms (44 pounds), respectively. However, gray snapper reach sexual maturity at about 2 years, 23 cm (9 in) and 0.3 kg (0.7 lbs) and are most often encountered by fishers at lengths ranging from 25 cm (10 in) to 60 cm (24 in).

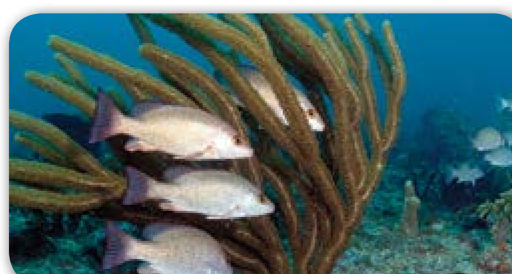
One of most popular game fish in south Florida, the gray snapper inhabits a predictable sequence of habitats over the course of its life cycle. Adults reproduce at the offshore periphery of coral reef habitats, dispersing their eggs and larvae in oceanic waters, where they can be transported by currents over large distances. After a short time in pelagic waters, larvae settle in the coastal bays and estuaries, which provide abundant food resources and shelter for their juvenile stages. Early juveniles primarily occupy seagrass habitats, feeding mostly on small invertebrates, such as worms and grass shrimp. After about a year, late juveniles have outgrown the safety of the seagrass blades and associate with mangrove prop roots, which provide prey species of killifishes and silversides and protection from large shoreline-patrolling predators (e.g., lemon sharks).



J. Luo - UM/RSMAS

Red mangrove prop roots are an important habitat for late juvenile gray snapper.

Mangroves tend to be the habitat with the highest concentrations of gray snapper, especially during daylight hours, hence their local name: mangrove snapper. At night, gray snapper disperse from the prop roots to adjacent seagrass beds where they forage on pink shrimp, blue crab, and other small invertebrate and fish prey. Electronic tagging and video surveillance studies indicate that after these nighttime feeding forays, they return back to their daytime "resting" sites in the mangroves the following morning. Mangroves also appear to serve as staging areas for mature individuals to congregate prior to movement to offshore coral reef habitats, where spawning takes place and the life cycle is repeated.



J. Marino

Gray snapper at Lighthouse Ledge Reef, off Boca Raton, Florida.

The gray snapper is one of several habitat-shifting species that occupy a suite of south Florida habitats depending on life stage, time of day, and season. Their life history strategy of using multiple habitats that span from oceanic, blue waters to shallow, protected shorelines demonstrates biological connectivity among watershed, bay, and offshore marine ecosystems. This connectivity underscores the importance of protecting multiple, contiguous habitats to effectively conserve habitat-shifting species and properly manage the fisheries that depend on them.

Fish tagging reveals bonefish and tarpon migratory patterns

Jerald S. Ault

Anglers have long wondered: "Where do big tarpon and bonefish come from and where do they go? Do populations of the species migrate internationally? And, why have populations declined or increased over years in different regions?" The answers to these questions are fundamental to determine the unit stock that is appropriate for management to ensure sustainability of the regional fisheries. Unfortunately, but typically, much more is known scientifically about commercial food fishes than species less desirable for human consumption, such as tarpon and bonefish. However, the confluence of their escalating economic importance, new technologies, and pressing interests in conservation of the species has recently opened a window of opportunity for improved understanding of the connections between tarpon and bonefish fisheries in U.S. waters and those of the Caribbean Sea.

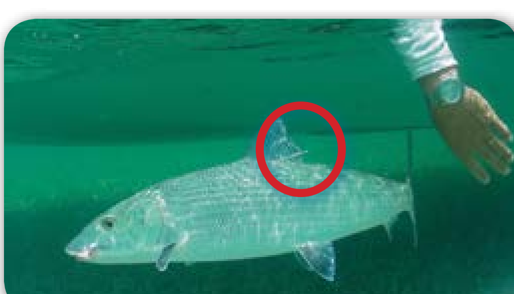
Bonefish

One step to ameliorate this problem for a previously believed local population of incredible economic significance was to start a bonefish anchor-tagging program in the Florida Keys as a collaboration among the University of Miami Bonefish and Tarpon Conservation Research Center, the Florida Keys Professional Fishing Guides Association, and the Bonefish and Tarpon Trust. While tagging projects are commonly used to provide information on fish movements, they can also provide a lot more, such as estimates of stock mortality, growth, recruitment, population size, and essential habitats of juveniles and adults. This type of vital information is needed to manage and conserve the valuable bonefish population in Florida. Since its inception in 1998, this joint effort has resulted in more than 7800 tagged bonefish with slightly more than 300 recaptures. These data provide fascinating and unprecedented information on bonefish movements and migrations that were previously unknown.

J. S. Ault - UM/RSMAS

Observed movements and migrations of bonefish tagged in the Florida Keys.

Overall, 42% of the recaptures took place at the same location where the fish was tagged, and about 70% were recaptured within 8 kilometers (5 miles) of the tagging location. However, do not let this fool you. Just because the fish are caught at or near the same location does not imply that bonefish do not move. Anchor-tag technology generates information on where the fish were tagged and recaptured; it provides no information about the intervening time between tagging and recapture. Notably, 16 recaptures were verified to have moved at least 80 km (50 mi) from where they were tagged. The longest movement recorded within Florida was for a bonefish



J. S. Ault - UM/RSMAS

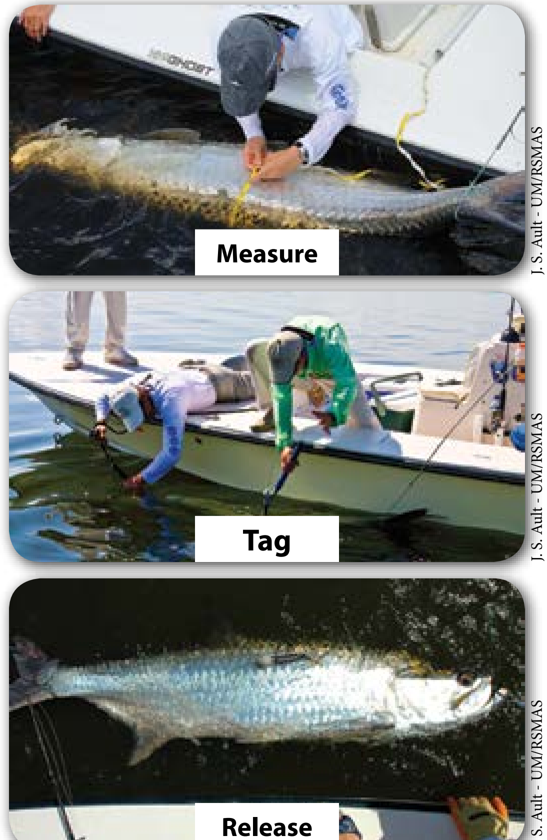
An anchor-tagged bonefish is ready for release. The tag shown just below the dorsal fin (circled in red) bears a unique identification code and contact information for reporting location of recapture and size of the fish.

Animal Diversity

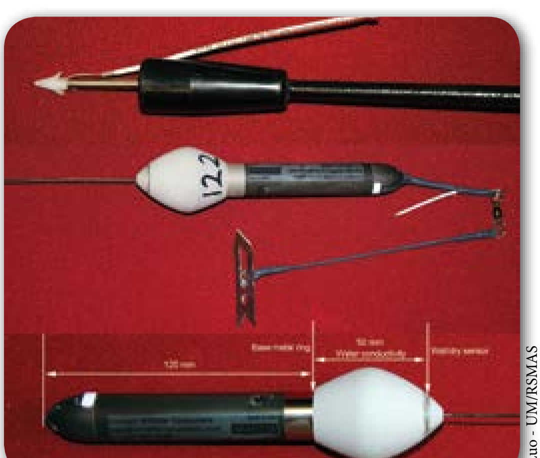
tagged in Biscayne Bay by Capt. Joe Gonzalez that was recaptured 5 months later by Steve Gray 203 km (126 mi) away at Sawyer Key in the Lower Florida Keys. Remarkably, two bonefish tagged in Florida moved across the Florida Current in the Florida Straits to be recaptured about a year later near Andros Island, Bahamas, more than 242 km (150 mi) least linear distance from where they were tagged! These data clearly indicate that not only do Florida bonefish frequently move around, but occasionally they mingle with their international neighbors.

Tarpon

Atlantic tarpon migration research was motivated by a very simple question, "Are our tarpon 'their' tarpon?" Anglers had observed firsthand the slaughter of large mature tarpon in many Latin American countries and wondered whether those impacts were responsible for the substantial declines of Florida regional tarpon fisheries. Pop-up archival transmitting (PAT) tags have been used since 2001 in collaboration with the Bonefish and Tarpon Trust to define tarpon migratory patterns, spawning and feeding areas, and population connectivity within the southeastern U.S., Gulf of Mexico, and Caribbean Sea. The



Sequence of steps involved in measuring, tagging, and releasing tarpon with a satellite-tracked PAT tag.



Comparison of conventional anchor tag (top) to state-of-the-art satellite-based pop-up archival transmitting (PAT) tags used to determine tarpon migrations, spawning locations, and ocean habitat use.

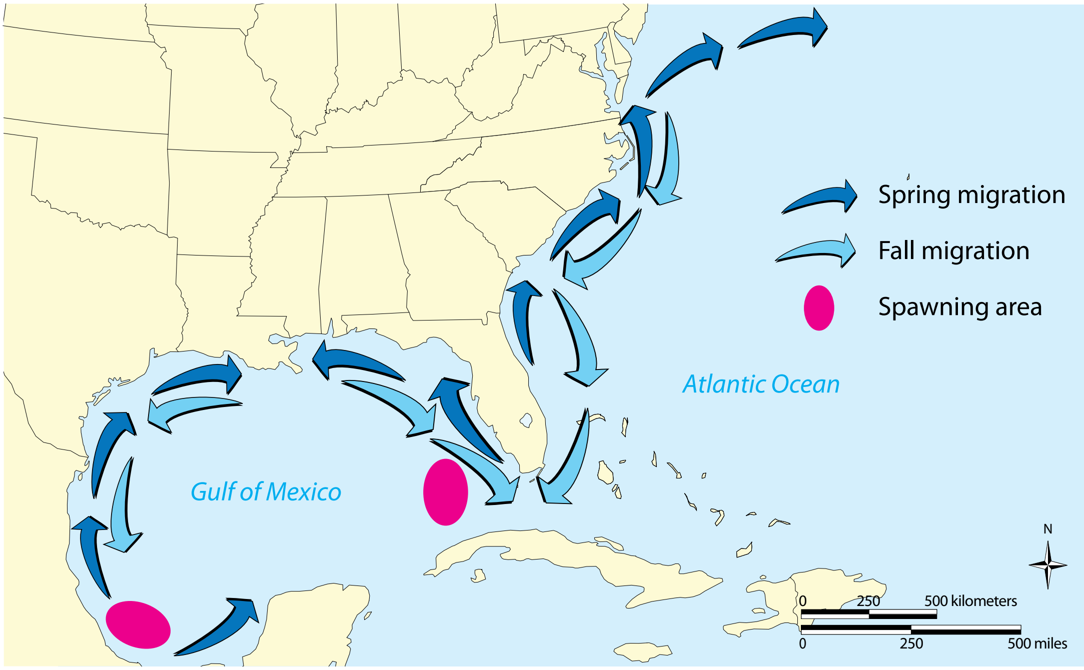
data are assessed for improved regional fishery management.

The PAT tags deployed on tarpon can collect and archive second by second data on depth of the animal, water temperatures, light levels, and salinity. Unlike conventional anchor tags requiring the recapture of tagged fish, PATs can be preprogrammed to automatically release from the fish at a specific date and time, usually about 6 – 8 months after deployment. When they pop up to the surface, they transmit compressed versions of the stored information to a network of orbiting satellites. All of this information is forwarded to computers at the University of Miami Bonefish and Tarpon Conservation Research Center laboratory for detailed analyses. While physical recoveries of deployed PAT tags are not necessary, when the tags are found, the entire data archive can be downloaded. A comparison of environmental data allows estimated locations of the tagged fish along their migration routes.

PAT tagging research has shown that migrating tarpon have an innate desire for water temperatures of 26°C (79°F). Tarpon seek this temperature band almost magically. They can suddenly materialize, seemingly overnight, in good habitats with food in this attractive water temperature. How tarpon know where and when to locate such specific temperatures is quite a mystery. It is now known that tarpon frequently travel hundreds to thousands of miles between seasonal spawning and feeding sites, sometimes in time periods as short as 2 months. For example, tarpon tagged in the southern Bay of Campeche, Mexico in May have reached Louisiana and Mississippi waters by July and August; tarpon tagged in the Florida Keys in late May have reached the Chesapeake Bay by late July; and tarpon tagged in Trinidad have ventured north of Martinique in the Windward Antilles Islands.

Migrating tarpon typically arrive in the Lower Florida Keys in mid-April, but this is highly controlled by water temperature. They are probably coming from the Caribbean Sea (i.e., Cuba, Yucatán, Belize, Honduras, Nicaragua, and Costa Rica). Determining their exact point of origins and route is a question that forms the next critical frontier for future tagging research.

Satellite-based tagging research has shown that tarpon undergo extensive long-range migrations throughout the Gulf of Mexico, southeastern Atlantic U.S. coast (seasonally as far north as Virginia), and Caribbean Sea. This means that all these tarpon fisheries rely on a single, shared regional population. Thus, a sustainable future for this fishery requires an integrated regional, national and international management strategy. Tarpon are valued for different reasons in different countries and by different cultures. This reality requires a unique blend of extensive international cooperation between anglers, guides, scientists, and fishery management agencies to ensure their sustainability.



Summary of migrations of tarpon in the Gulf of Mexico and southeastern United States determined by use of pop-up archival transmitting (PAT) tags.

Healthy tarpon and bonefish populations are important to the economy of south Florida

Jerald S. Ault

Atlantic tarpon (*Megalops atlanticus*) and bonefish (*Albula vuples*) are two of supreme challenges for sport fishing. Few fish species can match the speed of bonefish, or the brute strength, airborne acrobatics, or hair-raising power surges of tarpon. These two fish species have endured eons of severe environmental changes. Hooked-up with either, fishermen feel the unbridled survival instincts of two creatures that have survived for over 100 million years. Florida, the "fishing capital of the world", accounts for more than two thirds of the standing world records for tarpon and bonefish published by the International Game Fish Association in 2009. South Florida tarpon and bonefish fisheries alone annually support a multibillion dollar regional economy. However, the future sustainability of these precious fisheries is a challenge.

Tarpon

Atlantic tarpon, the "Silver King", has reigned supreme for more than a century as one of the most sought after inshore game fishes. Tarpon sport fishing contributes more than $6 billion annually to the regional economies of the coastal southeastern United States and Gulf of Mexico, providing livelihoods for tens of thousands of Americans from Virginia to Texas. The deep cultural roots of the United States tarpon fishery are reflected in numerous books, magazines, and photographic records published in the late 19th and early 20th century that depict the "glory days" of tarpon fishing.

P. Ford - patfordphotos.com

The Silver King, the most perfect and ancient sportfish, performs one of its trademark acrobatic leaps for a thrilled angler.

D. DeMaria

Schooling tarpon at Bahia Honda, Florida Keys, Florida.

Additionally, a presidential tradition of tarpon fishing, from Franklin D. Roosevelt in Port Aransas, Texas in the 1930s to more recently George H.W. Bush in the Florida Keys, underscores the broad appeal and historical importance of the fishery. Today, the United States fishery is a magnet for both domestic and international anglers: 61% of the current International Game Fish Association world records for tarpon come from the Florida Keys.

Despite the long history and growing importance of the tarpon recreational fishery, the species has declined throughout its range and faces growing challenges that require additional management coordination and federal protections to ensure that the United States fishery is sustained for future generations. Tarpon can live in excess of 80 years and grow to well over 113 kilograms (250 pounds), making them especially susceptible to overfishing. Although primarily a catch and release fishery in the United States, the sustainability of the tarpon fishery is under increased threats, and evidence of nonsustainable domestic fisheries already exists.

Port Aransas, Texas was once known as the "Tarpon Capital of the World" in the 1950s for its exceptional fishery. However, the fishery has declined so much that today the catch of a single tarpon warrants special mention. Although there are numerous possible causes for this collapse, overharvest was likely a principal contributing factor. During the heyday of the fishery, tarpon were typically killed for trophies or photos. All tarpon harvests are now prohibited (excluding special exemption for record catches), but the Texas fishery has not recovered.

Tarpon utilize a range of habitats throughout their life history. Juveniles are found along mangrove-lined coasts and salt marshes, and move to protected estuaries and lagoons in subsequent years. Mature adults occur on tidal flats and coral reefs, as well as within inlets and other coastal waters. These critical habitats are being degraded regionally at alarming rates. Loss of essential nursery habitats is especially troublesome. Since it takes about 10 years for tarpon to reach sexual maturity and enter the fishery, impacts of the loss of juvenile habitat are not realized for at least 10 years. This fact creates a substantial challenge to fishery recovery and sustainability. Identification and protection of critical habitats represents a sound investment in the future of the fishery.

Outside waters of the United States, fishing pressures for tarpon are intense and remain largely unregulated. For example, in Mexico, which serves as an important conduit for seasonally migrating tarpon that enter the United States fishery, tarpon are a focus of subsistence and commercial fishing. In addition, numerous decades-old "recreational" tournaments are held each year in which thousands of large, mature tarpon are killed, eliminating their reproductive contributions to future generations of the fishery.

How much is a single bonefish worth to the Florida economy?

Would you believe $75,000 per fish? That is not the prize value of a single fish caught during a fishing contest. It is the value of every bonefish larger than 35 centimeters (14 inches) swimming in Florida saltwater flats! That value is based upon a combination of population studies and tourism dollars, making Florida bonefish perhaps the most valuable fish in the world. This species is dear to the fishing guides who make their living hunting them and the anglers who are pursuing their dreams.

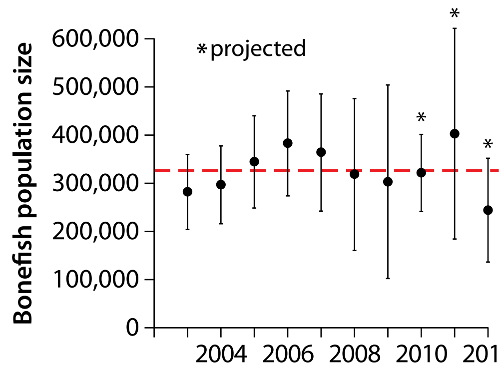
Bonefish

Bonefish, the "Gray Ghost" of tropical flats, are a popular saltwater game fish due to their occurrence in crystal clear, shallow tropical waters and their lightning speeds when hooked. These attributes support a catch and release fishery for the species around the globe. South Florida hosts the most popular recreational bonefish fishery in the world because of the availability of large fish. This is reflected by the fact that more than 68% of the saltwater fly rod and saltwater line class world records for bonefish were caught in south Florida coastal waters. This popular fishery contributes approximately $1.0 billion annually, making it a key component to the regional economy of south Florida.

The presence of bonefish is an excellent indicator of the general health of the ecosystem as they are the marine equivalent of the "canary in the coal mine." Where bonefish thrive, it can be assumed the entire coastal ecosystem is in good shape, assuring good fishing for all fishes. However, knowledgeable resource users report a decline in the bonefish population over the past 20 years. Despite the economic significance the bonefish fishery in south Florida, it is surprising that the stock has never been adequately assessed. The fishery is catch and release with no commercial harvest, therefore no records on catches are available as in other fisheries (e.g., snapper-grouper).

A satisfied angler proudly displays a 5.4 kilogram (12 pound) bonefish caught in the Florida Keys.

In 2003, the University of Miami, in collaboration with the Bonefish and Tarpon Trust, initiated an annual bonefish survey to determine a baseline for scientifically evaluating changes in the Florida Keys bonefish population. Bonefish are fairly easy to count on the flats, and fishing guides and their customers participate in the survey and count and report the quantities of bonefish observed and caught. Although quite variable, the Florida Keys population has averaged approximately 326,000 fish since 2003.



Bonefish population size estimated from the annual Florida Keys bonefish population census. Population has averaged approximately 326,000 fish since 2003. The red dotted line represents the long-term population mean.

The goliath grouper is a gentle giant

Sarah Frias-Torres

The goliath grouper (also known as jewfish), *Epinephelus itajara*, is the largest Atlantic grouper (Serranidae), and one of the two largest grouper fish in the world, exceeding lengths of 2 meters (6 feet) and weighing up to 450 kilograms (1000 pounds). Its specific name (itajara) means "Lord of the Rock" ("ita" = rock, "jara" = lord) which provides a vivid, accurate description of this magnificent reef fish. The species is found in tropical and subtropical latitudes of the eastern and western Atlantic Ocean.

J. S. Ault - UM/RSMAS

The goliath grouper is not afraid of divers. In the late 1980s, they were nearly driven to extinction by overfishing and spearfishing. They are now protected from harvesting by State of Florida and federal laws. These gentle giants offer a unique wildlife encounter opportunity.

Goliath grouper are extremely vulnerable to overfishing and extinction due to a combination of life history traits typical in large groupers (i.e., *Epinephelus*, *Mycteroperca,* and *Plectropomus*), such as slow growth, long life (exceeding 40 years), late sexual maturity (5 – 8 years), strong site fidelity, and formation of spawning aggregations. In addition, goliath groupers are not afraid of divers, which makes them extremely easy targets for spearfishing, further increasing their vulnerability to overfishing.

Fact or fiction?
The lobster monster

There is a common myth that goliath groupers are major predators of Caribbean spiny lobster and as the grouper population in Florida begins to recover from commercial extinction in the late 1980s, they will contribute to declines in the lobster population. Goliath grouper do eat lobster, as part of a mostly invertebrate diet, which also includes shrimps, crabs, gastropods, as well as slow-moving fish (e.g., stingrays catfish, cowfish, burrfish). In fact, Caribbean spiny lobster are part of the diet of at least 26 different animal species including invertebrates, elasmobranchs (i.e., sharks and rays), teleost fish, reptiles, and marine mammals. Humans, not goliath groupers, are mostly responsible for overall declines in lobster populations, due to overfishing, habitat destruction, and marine pollution.

Goliath grouper is a mangrove-dependent reef fish. Red mangroves are a critical nursery habitat for juvenile goliaths. As they grow and mature, they migrate to coral reefs, reef/rock ledges, and other hardbottom structures in the ocean, from shallow inshore areas to depths no greater than 50 m (150 ft).

Dwindling population numbers reached commercial extinction in the late 1980s. A federal and state fishing ban went into effect in Florida in 1990, followed by a ban for United States Caribbean islands and territories in 2003. Elsewhere in its range in the Caribbean, goliath grouper are critically endangered according to the International Union for Conservation of Nature Red List of Threatened Species.

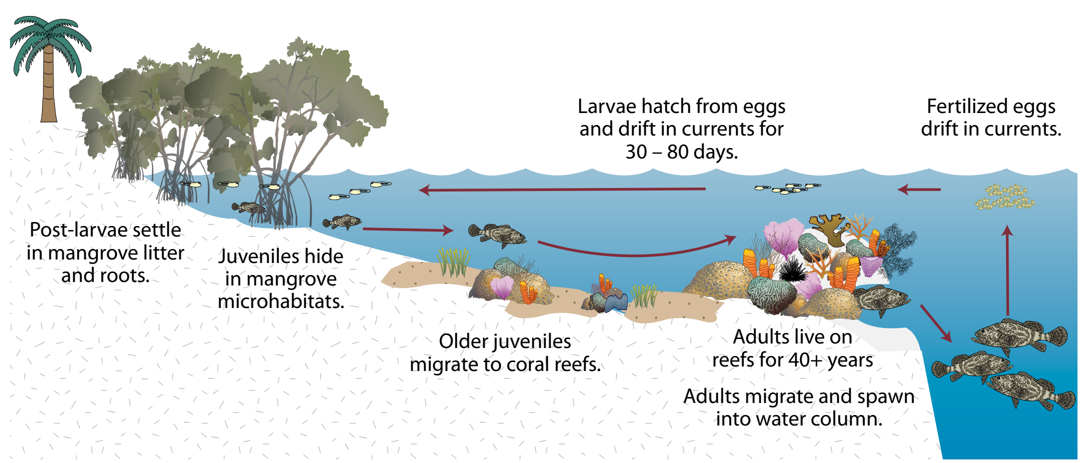
The life cycle of the goliath grouper connects mangroves and reef habitats

Sarah Frias-Torres

Once a year, during the full moon of August and September, all of the adult goliaths in the region aggregate at a very limited number of spawning sites to reproduce. Historically, thousands of very large individuals congregated. Today, recovering aggregations in Florida have been observed in the range of 10 – 100 individuals. No actual mating occurs; rather, males and females pair up or a male may court several females in preparation for the spawning event. Spawning includes the release of eggs and sperm into the water column, where fertilization occurs. After the full moon of September, the goliaths migrate back to their home sites, where they remain until they congregate once again the following year.

The fertilized eggs drift in the ocean for up to 40 hours, when "comma-sized" fish larvae hatch and continue drifting in the open ocean for between 30 – 80 days, potentially traveling hundreds of miles on ocean currents. During this time, the worm-like fish larvae grow into miniature, almost transparent, carbon copies of their parents. Scientists are uncertain how the baby fish locate their mangrove juvenile habitat, but eventually settlement occurs in the submerged red mangrove habitat that consists of tightly packed prop roots, attached algae, and dead leaves. Juveniles spend 5 – 8 years of their life in the mangrove habitat, expanding their preferred microhabitat as they grow to include overhangs, undercuts, solution holes, and submerged dead trees. The goliath grouper is one of the few groupers in the world able to live in brackish water and tolerate low oxygen levels, at least as juveniles.

When they reach about 1.2 meters (3.6 feet) in length, juveniles migrate to the coral reef and become sexually mature adults. This is known as an ontogenetic habitat migration. In the absence of coral reefs, juveniles exiting the mangroves will migrate to isolated patch reefs, reef/rock ledges, and artificial structures. Both juveniles and adults show a strong site fidelity, a specific "home" where they return daily to rest after their foraging trips.



Schematic of goliath grouper life cycle and movement of various life stages throughout the nearshore and reef environments.

Recovery of the goliath grouper populations is a unique conservation opportunity

Sarah Frias-Torres

The historical geographic distribution of goliath grouper in the western Atlantic and Caribbean basins is from North Carolina to Sao Paulo, Brazil. However, suitable mangrove and reef habitat availability controls the latitude limits where successful reproduction and development presently occurs. Thus, if the presence of fringing red mangroves is used as a proxy for juvenile goliath grouper habitat, and reef sites where adult groupers have been observed since 2000 as an indicator of adult habitat, the distribution of goliath grouper outside Florida and throughout the Caribbean Sea is rapidly shrinking. This is due to widespread habitat degradation, as well as continued overfishing, particularly the specific targeting of spawning aggregations. Therefore, the future of goliath grouper throughout its distribution range remains uncertain.

In 2002, Brazil initiated a fishing ban and its effects on grouper recovery there are still under evaluation. In spite of much habitat destruction due to coastal development and major alterations of freshwater flow, south Florida contains an extensive network of fringing red mangrove shorelines, concentrated mostly in the Ten Thousands Islands, the mangrove channels of the Florida Keys National Marine Sanctuary (the "Backcountry"), and parts of the southeast coast (Biscayne National Park and the Indian River Lagoon system). This is the historical nursery habitat for the goliath grouper in Florida. South Florida also contains the only continuous coral reef tract in the continental United States. The existence of both mangroves and coral reefs in south Florida, in combination with the federal fishing ban on goliath grouper, has allowed for a slow return of the species to its original distribution area throughout Florida. However, the recovery of the species is still underway.

The fact that Florida goliaths are slowly increasing in numbers, while populations have been steadily decreasing in other locations in the western Atlantic and Caribbean, weakens the argument that the Florida population is "fueled" by the arrival of goliath larvae from elsewhere in the Caribbean by ocean currents. The lack of genetic connectivity between Florida and Caribbean populations has not yet been conclusively demonstrated, but evidence based on population dynamics strongly suggests that the Florida goliath grouper population is a Distinct Population Segment within the overall distribution area of the species and relies on self recruitment from the two known spawning aggregation sites, one in the Gulf of Mexico and one in southeast Florida, near the town of Jupiter.

Although south Florida is one of the few regions in the world where all life stages of goliath groupers, including their spawning aggregations, can be observed, the goliath population in Florida remains vulnerable. Poaching (illegal catch) occurs and dead goliaths with signs of poaching have recently been found at the spawning aggregation site in southeast Florida. Harmful algal blooms are a powerful stressor in limiting the full recovery of the Florida goliath grouper population. A red tide bloom (*Karenia brevis*) in 2005 resulted in at least 50 confirmed goliath grouper deaths based on the carcasses that washed ashore along the west Florida coast. Ninety-five percent of the dead groupers were of adult size, and the total number of dead fish could be much higher because other carcasses might have been lost in the ocean.

An effective public awareness campaign on the habitat requirements and the vulnerability of goliath groupers to other stressors is required to ensure the successful recovery of this keystone species.

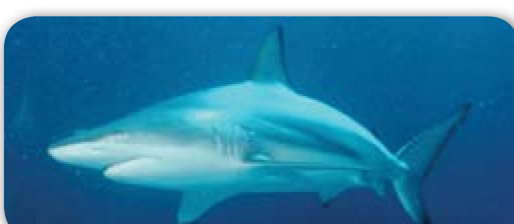
Many species of sharks are found in south Florida waters

Jeremy J. Vaudo and Michael R. Heithaus

The coastal waters of south Florida are home to several shark species, and additional species may be encountered in offshore waters. Some of the most common species are described, including one ray, a close relative of sharks. Also included is a list of other species of sharks and rays that may be encountered.

Wikimedia

Bull shark (*Carcharhinus leucas*). The bull shark is one of the most common large sharks of south Florida. It is found in tropical and subtropical waters throughout the world. Bull sharks are one of the few shark species that can tolerate freshwater, and coastal bays and rivers serve as nursery areas. At 3 – 5 years old, they move into shallow coastal waters, including Florida Bay. Adults are found along open coasts, near reefs, and in tidal passes and reach lengths of 3.4 meters (11 feet). Pups are born in late spring and early summer.



Wikipedia

Blacktip shark (*Carcharhinus limbatus*). This species is found in tropical and subtropical nearshore waters around the world. Young blacktips are often found in shallow bays and estuaries. Adults rarely reach lengths of 2 m (6.5 ft) in length in the southeastern United States and females have a 2-year reproductive cycle. Although pupping occurs in many south Florida bays during the summer, the species is known to make seasonal migrations, forming large aggregations in Georgia and the Carolinas in the summer, and returning to Florida in the fall.

N. Hammerschlag - UM/RSMAS

Tiger shark (*Galeocerdo cuvier*). The tiger shark is a coastal-pelagic species found worldwide in tropical and subtropical waters. Although associated with coastal areas, tiger sharks sometimes make excursions into oceanic waters. They are capable of reaching 5.5 m (18 ft) in length. Females give birth every 2 or 3 years. They were once more common in south Florida and their population was negatively impacted by fisheries in the Florida Keys before World War II.

NOAA

Nurse shark (*Ginglymostoma cirratum*). This species is found in the warmer waters of the Americas and western Africa. It is probably the most common large shark found in south Florida, especially in the Florida Keys. Adults can be up to 3 m (9.8 ft) in length and are found around reefs, mangrove keys, and on sandflats and seagrass meadows. Nurse sharks are nocturnal and are often seen resting on the bottom in groups during the day. Mating occurs in shallow waters during June and July and pups are born in November and December. Females have a biennial reproductive cycle.

Wikimedia

Lemon shark (*Negaprion brevirostris*). Lemon sharks are found in tropical and subtropical waters of the Atlantic and eastern Pacific Oceans and are adapted to tolerate warm, low oxygen waters, such as Florida Bay. Juveniles are common aroud mangrove islands and the Florida Keys and adults can be found in coastal waters, including coral reefs. Individuals can reach lengths of 3 m (9.8 ft). Females have a 2-year reproductive cycle and return to their natal grounds to give birth. Pupping occurs in late spring through early summer. During winter, adults form aggregations, possibly to mate, and migrate north as waters warm. Lemon sharks are protected in Florida waters.

R. Lupo Dion - sharksavers.org

Great hammerhead shark (*Sphyrna mokarran*). The great hammerhead is a coastal-pelagic shark found in tropical and subtropical waters worldwide, usually in open waters over the continental shelf. However, at times it can be found very close to shore. It is the largest of the hammerhead sharks and can reach a length of 6 m (19.7 ft). Hammerheads are observed in south Florida to eat large tarpon and sometimes use their hammer to pin rays to the bottom before eating them. Of the shark species that have been accurately aged, this species has one of the longest life spans, with individuals reaching 40 years old.

Wikimedia

Smalltooth sawfish (*Pristis pectinata*). The smalltooth sawfish is in the ray family, but has a shark-like body. It is a critically endangered species that historically ranged from New York to Brazil. Currently, it can only be found in substantial numbers in coastal and estuarine waters of southwestern Florida and parts of the Florida Keys. Adults can exceed 5 m (16.4 ft) in length. Sawtooth sawfish are highly susceptible to gill nets that contributed greatly to their decline. It was listed by Florida as an Endangered Species in 1992 and placed on the federal endangered species list in 2003.

UM/RSMAS/CUFER

Bonnethead shark (*Sphyrna tiburo*). Bonnetheads are found in tropical and subtropical water of the Americas. They are typically associated with shallow, softbottom habitats and seagrasses. Bonnetheads are the smallest of the hammerhead sharks and rarely exceed 1 m (3.3 ft). Mating occurs in late October – Novmber, although females do not ovulate until April – May. Pups are born in August, giving bonnetheads the shortest known gestation period of viviparous (live-bearing) sharks.

NMFS

Atlantic sharpnose shark (*Rhizoprionodon terranovae*). The Atlantic sharpnose shark is found in warm and temperate waters of the Atlantic coast of North America and Brazil. It inhabits nearshore waters, including bays, estuaries, and sand beaches, but moves further offshore in winter. The maximum size is 1.1 m (3.6 ft), but most are less than 1 m (3.3 ft) in length. Pups are born in late spring and early summer.

Some other sharks and rays found in south Florida

Spinner shark: *Carcharinus brevipinna*
Blacknose shark: *Carcharinus acronotus*
Caribbean reef shark: *Carcharinus perezi*
Sandbar shark: *Carcharhinus plumbeus*
Fintooth shark: *Carcharhinus isodon*
Silky shark: *Carcharhinus falciformis*
Scalloped hammerhead shark: *Sphyrna lewinia*
Spotted eagle ray: *Aetobatus narinari*
Southern stingray: *Dasyatis americana*
Atlantic stingray: *Dasyatis sabina*
Yellow stingray: *Urobatis jamaicensis*
Cownose ray: *Rhinoptera bonasus*
Atlantic guitarfish: *Rhinobatos lentiginosus*

Sharks are vulnerable to overfishing

Jeremy J. Vaudo and Michael R. Heithaus

Shark reproduction

Reproduction in sharks is very different than reproduction in most bony fishes, and that fact has important implications on the ability of sharks to withstand intense fishing pressure. In most bony fish, reproduction takes place external to the fish body and large quantities of eggs and sperm are released into the water column, where fertilization takes place. Sharks, on the other hand, have internal fertilization and produce far fewer eggs and offspring.

Depending on the species, fertilized shark eggs are either internally retained by females (i.e., live-bearing sharks) or shed for development outside the body in a leathery egg case (i.e., egg-laying sharks). Egg-laying sharks tend to be small, bottom-dwelling species. There are no-egg laying sharks in coastal waters of south Florida.

There are two kinds of live-bearing sharks, those where there is no direct connection between the mother and the embryos in the uterus (aplacental viviparity), and those where the yolk sac becomes vascularized and attaches to the uterine wall, similar to a mammalian placenta (placental vivipary). Most common sharks in south Florida exhibit placental vivipary. Brood size in both types is very low, with either one or two pups in each breeding cycle.

In some aplacental viviparous sharks, the developing sharks eat unfertilized eggs within the uterus. Sand tiger sharks take this one step further, and the largest embryos eat smaller embryos within the uterus until just one embryo remains.

Because of their relatively large size and advanced development at birth, newborn sharks are well suited for survival, but are preyed upon by large fish, and especially by other sharks. Juvenile sharks of many species make use of shallow coastal waters of south Florida as nursery areas that offer protection from large predators. Juvenile bull sharks can even be found in freshwater reaches of many coastal rivers.

Shark vulnerability

Sharks grow slowly and mature relatively late in life. Many large species do not mature until they are 10 or more years old. In addition, because of the long gestation periods required for the development of their large offspring, many species only give birth every other year. These life history traits make sharks populations particularly vulnerable to overfishing because of a low potential to rebound from large population losses: individuals can not be replaced as quickly as they are removed.

As a result, shark populations around the world have experienced large population declines. In many areas where sharks were common 50 years ago, it is now rare to observe a shark and even rarer to see a large shark. In some areas, studies have documented declines in shark numbers of more than 90%. In the 1920s and 1930s, large sharks, including tiger sharks, were common in the Florida Keys and supported a lucrative coastal fishery. Today, large sharks are rare in the Keys and the species composition has apparently changed. How the loss of large sharks has effected the trophic dynamics of coastal ecosystems is currently the focus of considerable research efforts.

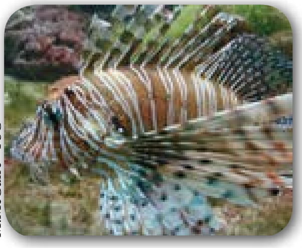

NOAA

"Finning" is the practice of cutting off the fins of a shark for food and discarding the rest of the body. This is a wasteful and cruel practice that contradicts the principles of sound fisheries management and conservation.

Exotic lionfish have invaded south Florida waters

Maia McGuire

Invasive species are plants and animals that exist in an area where they are not native. Their introduction has a negative impact on ecosystem health, and the cost of their control and management in the United States is estimated to exceed $120 billion annually. Florida ranks among the top three states in the number of invasive species and the negative economic, environmental, and quality of life impacts that they cause. According to the Florida Fish and Wildlife Conservation Commission, over 400 nonnative fish and wildlife species have been documented in Florida. Most nonnative fish and wildlife species find their way into Florida habitats through escape or release by pet owners. Since 1999, 16 nonnative marine fish species have been documented in Florida coastal waters. With one possible exception, all of these fish were imported in the marine aquarium trade and were introduced into the wild as a result of accidental or deliberate release by aquarium hobbyists.



M.McGuire - FSG

Lionfish is an invasive exotic marine species found in south Florida, the Western Atlantic, Bahamas, and Caribbean basin.

Lionfish (*Pterois volitans* and *Pterois miles*) are native to the Indo-Pacific region and are now increasing in range and abundance throughout the Caribbean, western Atlantic Ocean, and Gulf of Mexico. Lionfish have showy, striped fins, several of which contain venomous spines. Their initial introduction was likely the result of accidental or deliberate dumping of aquarium specimens, probably in south Florida.

The first Atlantic specimens of lionfish were reported from Biscayne Bay in 1992. Since 2000, the populations of lionfish have spread from coastal Florida, northward through the western Atlantic and into the Bahamas and the Caribbean Sea. In January 2009, the first lionfish was reported in the Florida Keys and since that time, many more lionfish have been sighted in the Keys.

Lionfish densities in some parts of the Caribbean far exceed those in their native Indo-Pacific region. Populations are expected to increase because there are few predators of lionfish in the Atlantic or Caribbean. Gut content analyses of lionfish reveal that their primary prey items are cleaner fish (i.e., wrasses), but that they also feed on juveniles of many fish species. Researchers in the Bahamas found that a single lionfish transplanted onto small patch reefs reduced native fish recruitment by nearly 80% on those reefs.

Be a responsible pet owner and help protect Florida native wildlife

It is illegal to release nonnative plants or animals in Florida because of their harmful effects on native wildlife. Instead of releasing unwanted pets, follow suggestions from Habitattitude, a national partnership among the pet industry, Sea Grant, United States Fish and Wildlife Service, and local partners:

- Contact a pet retailer and ask if the pet can be returned to the store.
- Contact local hobbyist clubs and ask if a member can give your pet a home.
- Contact local zoos or aquaria to see if they can adopt your pet.
- Contact a veterinarian or pet retailer to discuss humane disposal options.
- Check the Florida Fish and Wildlife Conservation Commission website for pet amnesty dates and locations (www.myfwc.com).

The Florida manatee is an icon of south Florida

Holly Edwards and Meghan Harber

The Florida manatee (*Trichechus mantus latirostrus*) is a subspecies of the West Indian manatee. Manatees are sometimes called "sea cows" because of their size and their languid pace. Adults can reach 4 meters (13 feet) in length and can weigh up to 1360 kilograms (3000 pounds). They are graceful swimmers and are found in coastal waters. Manatees never leave the water, but, like all marine mammals, they must breathe air at the surface. While resting, a manatee can remain submerged for up to 20 minutes. When swimming, they must surface for air more frequently.

C. Muenzer - Wikimedia

Florida manatees are found in coastal waters and rivers and eat seagrasses and other submerged aquatic vegetation.

Manatees have relatively little body fat despite their size and need warm water to survive in winter. They can not tolerate temperatures below 20°C (68°F) for long periods of time. Because of their susceptibility to cold, their distribution and range is directly associated with seasonal change. In summer, Florida manatees frequently occur alone or in small groups in rivers and coastal bays, but they can range as far as Texas and Massachusetts. In winter, manatees gather in groups in the natural springs of central and south Florida, particularly in springs flowing into the St. John's River and Crystal River. Warm water discharge from power plants can also attract large numbers of manatees in winter.

Individual manatees have no real core social group, but rather drift in and out of groups. However, when females are ready to mate, males will form mating herds and aggressively compete for the opportunity to mate with a female. The reproductive rate is low; on average an adult female gives birth to one calf every 2 – 5 years. Calves are born underwater and mothers must help them to the surface for their first breath. Their mothers will care for them for up to 2 years. Calves nurse underwater, but after a few weeks begin to eat underwater vegetation. Adult manatees are voracious grazers and can eat about a tenth of their own weight every day.

The fact that manatees are large and slow moving made them historically vulnerable to hunters. They were harvested for their meat, oil, and hides. Today, manatees are an endangered species protected under the federal Endangered Species Act and the Florida Manatee Sanctuary Act. Although protected, manatees still face threats, the most pressing of which are boat collisions and loss of warm water habitat. Many Florida manatees have propeller scars across their backs from being accidently hit by motorboats. Stringent conservation and protection measures are required to maintain the existing manatee population. Please slow your watercraft to idle speeds in areas posted with manatee warning signs.

USFWS - Wikimedia

Manatee calves are born underwater and are cared for by their mothers for up to 2 years.

Two dolphin species occur in Florida waters

Jessica Powell, Laura Engleby, and Meghan Harber

There are two species of dolphins commonly found in the waters of south Florida, the Atlantic bottlenose dolphin (*Tursiops truncatus*) and the Atlantic spotted dolphin (*Stenella frontalis*). As with all marine mammals, dolphins are protected by the Marine Mammal Protection Act.

In Florida, dolphins live in the same habitat in which people boat or recreate. Consequently, many dolphins around the state are at risk of being illegally fed or harassed by people. Not only are those activities illegal, but they cause dolphins to lose their natural wariness of humans. Dolphins are killed and injured each year as a result of being struck by boats or becoming entangled in or ingesting fishing gear. When dolphins are encountered in the wild, the National Marine Fisheries Service recommends staying 46 meters (150 feet) away and limiting viewing time to 30 minutes. If fishing and approached by dolphins, it is best to pull your lines out of the water and change fishing locations or wait for the dolphins to leave. Never feed wild dolphins—it is harmful and illegal.

Atlantic bottlenose dolphin

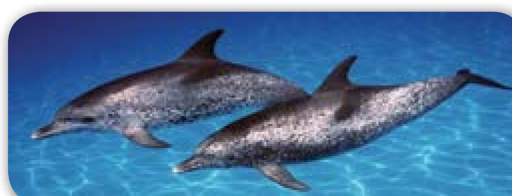
Dolphin Ecology Project

Atlantic bottlenose dolphins are common in bays, estuaries, and coastal waters of south Florida.

The bottlenose dolphin is one of the most common and well known dolphins. They live in groups that range in size from 2 – 15 individuals. Bottlenose dolphins consume a wide variety of prey, including fish and squid.

Dolphins sometimes use echolocation when hunting. A dolphin will emit a series of clicks and when the clicks hit an object, such as a fish, the sound waves bounce back and are deciphered by the dolphin, allowing the animal to determine the size, shape, and location of the object. Bottlenose dolphins also use their hearing to listen for potential prey opportunities. Dolphins use clicks and whistles, as well as leaps, tail slaps, and jaw popping to communicate to one another. Bottlenose dolphins can identify one another because each dolphin emits distinctive sounds known as "signature whistles."

Atlantic spotted dolphin



dolphindreamteam.com

Atlantic spotted dolphins are common offshore and along the continental slope of south Florida.

In the Gulf of Mexico and Atlantic Ocean, Atlantic spotted dolphins mainly reside in the shallow waters of the continental shelf. Spotted dolphins are typically smaller than bottlenose dolphins and are most identifiable by the speckles on their grayish body. Spots begin to develop after birth and eventually become fused with old age. A coastal group typically contains less than 20 individuals. The diet of spotted dolphins consists mainly of squid and fish. Large groups of spotted dolphins have been observed working together to herd fish into dense balls, trapping them against the surface. To herd fish, dolphins use bubbles, splashing, and tail slaps, as well as flashing their light-colored underside. This species of dolphin also has a complex communication system made up a number of different types of vocalization.

Bottlenose dolphins in Florida Bay can capture prey by corralling them in a mud ring

Laura Engleby

Bottlenose dolphins feed on a variety of fish and utilize many strategies to seek and capture prey. Bottlenose dolphins, as well as humpback whales and killer whales, are known to stir up bottom sediments while feeding. Cooperation among dolphins while searching for and capturing prey has also been reported. In Florida Bay, one feeding strategy bottlenose dolphins use is called "mud ring" feeding.

Dolphin Ecology Project

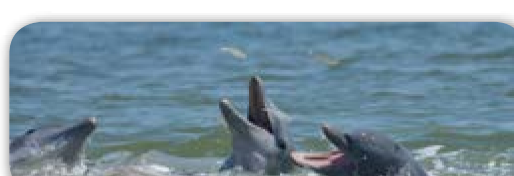
A mud ring created by a bottlenose dolphin in Florida Bay to corral prey fish.

Dolphins are often observed in small groups (2 – 8 individuals) herding fish prior to making a mud ring. The actual mud ring behavior itself is discrete, lasting less than one minute and usually occurs along shallow, inner basin mud banks in Florida Bay. Typically, one dolphin will stir up the bottom sediment by swimming in a counterclockwise direction, resulting in a ring-like mud plume (approximately 3 meters [9.8 feet] in diameter) on the surface. At the point when the mud ring closes, other dolphins appear, positioned outside the ring near the closure, side by side with heads facing towards the inner ring. The "ring maker" then joins the other dolphins. All the dolphin heads are either sideways at the surface or vertical and above the water with mouths open. Almost immediately, fish begin leaping from the ring, mostly oriented towards the portion of the ring where the dolphins are waiting. The dolphins catch the fish while they are airborne or wait for the fish to land in their mouths. Occasional bite sounds or squeals from the dolphins are audible above the surface.

During mud ring feeding, it remains unknown if cooperation occurs during the seeking of prey, but dolphins do appear to behave in a synchronized manner once prey have been found. Detailed examination of dolphin behavior occurring prior to mud ring feeding will provide further insights in this regard. In addition, the Dolphin Ecology Project plans to investigate the roles of individual dolphins. For example, are the same dolphins always the "ring maker" or does this vary?

It is also unclear if the mud ring is a byproduct of dolphin movement underwater, or if the mud ring is an active agent in herding the fish. Dolphins are also known to use the surface as a barrier when herding fish. Striped mullet (*Mugil cephalis*) are a primary prey species in Florida Bay. Since mullet are benthic feeders, they often stir up bottom sediment resulting in "mullet muds," suggesting that these fish would likely not be alarmed by plumes of mud. Therefore, it remains unclear if the mud triggers a fright response in mullet causing them to jump through the water surface and into the air. If that is the case, perhaps dolphins have learned to anticipate this predictable response in fish behavior.

The above work was conducted by the Dolphin Ecology Project under the National Marine Fisheries Permit General Authorization File No. 911-1466.



Dolphin Ecology Project

As fish leap over the mud ring, they are caught in the air and eaten by bottlenose dolphins.

There are five species of sea turtles in south Florida

William L. Kruczynski and Pamela J. Fletcher

There are five species of sea turtles found in waters of south Florida: loggerhead, green, leatherback, hawksbill, and Kemp's ridley. During summer months, it is estimated that there are approximately 50,000 turtles in Florida waters. Florida is the most important nesting area in the United States for loggerhead, green, and leatherback turtles. Hawksbill and Kemp's ridley turtles are not known to regularly nest in Florida.

Wikimedia

Loggerhead turtle (*Caretta caretta*). The loggerhead gets its name from its large, wide head with powerful jaws. It is classified as a threatened species. It is the most common sea turtle in south Florida and it is estimated that as many as 68,000 loggerhead nests are found in Florida each year. Loggerheads eat mollusks, crabs, and encrusting animals.

Nesting

Sea turtles nest on beaches typically from April – October with some variability depending on their species. A female typically nests every 2 or 3 years and can lay several nests during one nesting season. They dig nests with their back flippers and deposit about 100 eggs, each the size of a ping pong ball. They disguise their nest by flinging loose sand over it, and once a female leaves the nest she does not return.

Eggs incubate for about 2 months, then hatchlings make their way to the surface and emerge at night when the sand cools. Hatchlings scramble to open water and swim offshore, where they live for several years drifting with Sargasso weed. As turtles grow older, they swim into coastal waters.

Wikimedia

Green turtle (*Chelonia mydas*). The green turtle gets its name from it green-colored body fat. It is listed as an endangered species in Florida. Most greens nest in the Caribbean, but as many as 2000 nests can be found in Florida each year. It was hunted for its meat that was made into soup. Eggs are still harvested in some countries. Green turtles graze on seagrasses and are the only sea turtles to eat plants.

Threats

For centuries, millions of sea turtles roamed the oceans. However, in the past 100 years their numbers have been greatly reduced and all species are in danger of extinction. They have been hunted for their meat and eggs. Loss of nesting habitat and ocean pollution have also contributed to their decline.

A main danger to hatchlings is from artificial lighting. Hatchlings move toward the brightest direction, normally the sky over the ocean. However, artificial lights adjacent to beaches cause them to crawl in the wrong direction. Other dangers include obstructions on beaches that can block their path to the sea, and predators such as raccoons, dogs, and fire ants.

You can help

If you live near a beach, you can help by keeping outside lights off during turtle nesting season and closing your window blinds if light is visible from the beach. Remove chairs and other objects from the beach at night; level sand castles and fill any holes dug during the day. Use trash containers for all trash. Sea turtles mistakenly eat debris, particularly plastics, which often results in death. Never buy products made from sea turtles, including meat, soups, shell jewelry, or other items.

Wikimedia

Leatherback turtle (*Dermochelys coriacea*). The leatherback is an endangered species. It is the largest of the sea turtles and grows up to 2.4 meters (8 feet) in length. It has a rubbery dark shell with seven ridges that run the length of its back. They can travel many thousands of kilometers and dive hundreds of meters deep. They feed primarily on jellyfish and other soft-bodied animals. Ingestion of plastic bags and egg collecting are the prime reasons for population declines. About 200 leatherback nests occur in Florida each year.

C. Rogers - USGS

Hawksbill turtle (*Eretmochelys imbricata*). The hawksbill turtle is an endangered species and is named for its narrow beak. It was once common in Florida but now is very rarely seen here. It is a relatively small sea turtle, growing to about 87 centimeters (34 inches). They feed on sponges, jellyfish, and other invertebrates. Sponge predation by hawksbills may influence succession and diversity by freeing space on reefs for settlement by other benthic organisms. Their highly specific sponge diet makes them vulnerable to deteriorating conditions of coral reefs. Hawksbills have been hunted to near extinction for their beautiful shell. Japan and Cuba have exempted themselves from the Convention on International Trade in Endangered Species (CITES) ban on hawksbills. Other countries with hawksbills, such as Haiti, do not belong to CITES and offer shells for sale.

USFWS

Kemp's ridley turtle (*Lepidochelys kempii*). Kemp's ridley is the rarest and smallest of the sea turtles. They grow to about 71 cm (28 in). It is an endangered species and nests on a single beach in the United States at Padre Island National Seashore, Texas. They feed predominantly on crabs, but also eat jellyfish and sea stars. Many have died after being tangled in shrimp nets or from eating trash mistaken for food. The species is named after Richard Kemp of Key West.

Sea turtle facts

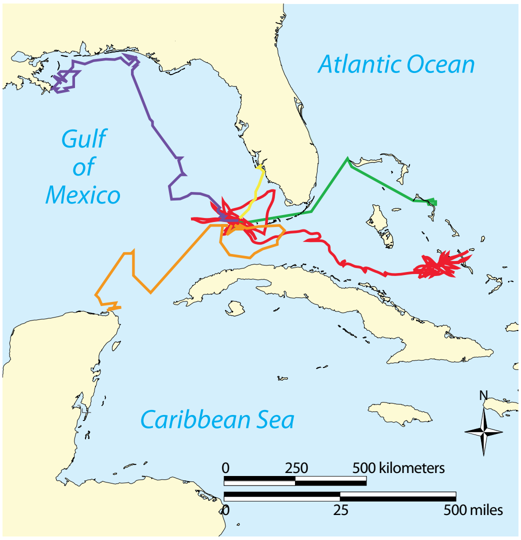
- Approximately 80% of the loggerhead turtles found in the United States use Florida beaches and nearshore waters.
- Sea turtles can migrate for thousands of kilometers, but they usually return to lay their eggs on the same beach where they hatched.
- Sea turtles have existed for over 100 million years.
- It can take 15 – 50 years before a sea turtle reaches reproductive age.
- Only one in a 1000 – 10,0000 turtle hatchlings will survive to adulthood.
- When it is time to sleep, loggerhead turtles sometimes wedge themselves under a rock close to shore or take a nap while floating on the surface in deep water.
- The nest temperature during incubation determines the sex of sea turtles. Cool conditions produce males; hot conditions produce females.
- Sea turtles have good underwater vision, but are nearsighted out of the water.
- Sea turtles do not have external ears, but they respond to low frequency sounds.

Adapted from www.seefloridaonline.com/turtles/

Satellite tagging of sea turtles provides information on their movements and habitat requirements

Kristen Hart

The three most common sea turtles in south Florida are loggerheads (*Caretta caretta*), greens (*Chelonia mydas*), and hawksbills (*Eretmochelys imbricata*). In the United States, green and hawksbill sea turtles are listed as endangered species and the loggerhead is threatened. These three species have different habitat needs for feeding. Loggerheads primarily forage on hardbottom areas for spiny lobsters and crabs. Green turtles eat seagrasses and marine algae, and hawksbills consume sponges on reefs.



Monitoring sea turtles using satellite tracking techniques allows scientists to learn more about their movements. This map shows the movement of individual turtles tagged in the Dry Tortugas and illustrates the regional connectivity of sea turtles in the wider Caribbean.

How much these species overlap and interact in south Florida is currently not well known. New observations and satellite tagging and tracking of turtles provides useful information on the ecological requirements and movements of the three species, and will be useful in the development of recovery plans and management strategies.

Everglades National Park

During a study at the Big Sable Creek mangrove complex on the southwest coast of Everglades National Park, more than 70 juvenile green turtles were observed in nearshore mangrove habitats and headwater streams. This is the first time that green turtles have been found in this habitat type. Dominant food items for juvenile green turtles in this area are red and green marine algae, rather than seagrass. During the time that young sea turtles spend in coastal creeks and nearshore habitats, they are probably exposed to human-derived nutrients and contaminants. Fibropapillomas (tumors) were observed on 58% of the juvenile green turtles sampled, but it is not yet known if tumor incidence is linked with degraded water quality or other stressors.

Dry Tortugas National Park

The sandy beaches of Dry Tortugas National Park provide nesting habitat for all three species and several life stages of the three species are observed in the Dry Tortugas. In 2007, a no-take marine reserve, called the Research Natural Area, was created in the Park to restore ecological integrity by minimizing human influences. The area is currently being mapped to quantify the distribution and amount of critical turtle habitats. Turtles have been captured at Dry Tortugas and outfitted with acoustic and satellite transmitters that allow scientist to track their daily movements to determine if they reside in the Research Natural Area year-round or only use the area periodically. It was found that all three species spend most of their time outside the Research Natural Area, but frequently pass through it. Some turtles tagged in the Dry Tortugas have been observed to migrate to Cuba, the west coast of Florida, and the Bahamas.

Crocodiles and alligators coexist in south Florida

Rebecca G. Harvey, Michael S. Cherkiss, and Frank J. Mazzotti

South Florida is the only location in the world where alligators and crocodiles coexist. The American alligator (*Alligator mississippiensis*) and the federally threatened American crocodile (*Crocodylus acutus*) are two of the 21 species of crocodilians found in the world, the last living descendents of dinosaurs. Crocodiles are much more rare than alligators in south Florida and, contrary to their reputation, they are shy animals that tend to avoid humans. In Florida, crocodiles are found primarily on the coasts in saltwater and estuarine habitats, while alligators favor inland freshwater environments. However, the two species sometimes occur side by side in areas such as the mangrove-lined estuaries found in Everglades National Park. Alligators and crocodiles are top predators that eat almost anything, including fish, birds, turtles, and small mammals. Increasing development in or near wetlands and coastal areas has led to more frequent encounters with both species, and it is crucial that residents and visitors exercise caution and never feed or harass these animals.

American crocodile

The American crocodile is found in tropical coastal habitats of Central and South America, Mexico, and the Caribbean, with south Florida at the northern edge of its range. Growth and survival of crocodiles in Florida are linked to regional hydrologic conditions, especially rainfall, water level, and salinity. Crocodiles thrive in healthy estuarine environments. They inhabit lakes, marshes, ponds, swamps, rivers, and creeks. Preferred nesting habitat is on elevated ground next to relatively deep water with low to moderate salinity, in protected areas away from human disturbance.

Crocodiles have always been rare in Florida. After crocodiles were declared endangered in 1975, protected areas were established in the three known nesting areas: northeastern Florida Bay in Everglades National Park, Crocodile Lake National Wildlife Refuge on Key Largo, and Florida Power and Light Company Turkey Point Nuclear Power Plant. Today, there are approximately 2000 crocodiles in Florida; they are considered to be an endangered species success story as their population is currently increasing.

American alligator

The American alligator ranges throughout the southeastern U.S. from Texas to North Carolina. Alligators were historically abundant in Florida but populations were decimated by hunting. They experienced a full recovery and were removed from the federal endangered species list in 1987. However, alligators are still considered a "species of special concern." They are a keystone species in the Everglades, meaning they affect nearly all aquatic life in the ecosystem. They build and maintain "alligator holes," depressions in the marsh that fill with water during the dry season and provide habitat for many species of plants and animals, including fish and wading birds.


W. Guzman - UM

American crocodiles
Grayish-green in color with tapered snout
Exposed fourth tooth on lower jaw
Rare and shy


M. Rochford - UF

American alligators
Darker in color with broader snout
No exposed tooth on lower jaw
Bold and more common

Sponges are an important component of the coral reef community

Joseph R. Pawlik

With the reduction of coral coverage, sponges now dominate many coral reefs in Florida. Approximately 20 species of sponges are commonly found. Their forms range from vases to long ropes to amorphous blobs, and their colors range from brilliant orange, blue, and pink to dull brown, gray, and black. You can learn to identify reef sponges species by using a web-based taxonomic guide at spongeguide.org.

Sponges play important roles in the coral reef ecosystem. They filter very large volumes of seawater, which results in increased water clarity. Filtration may also remove algae from the water column that may otherwise become overabundant and could result in harmful blooms. However, dense blooms of small-sized phytoplankton can clog sponge chambers and kill them. Sponges serve as homes for many reef invertebrates and fishes and they are eaten by brightly colored reef fish species, particularly angelfishes and parrotfishes.

J. Pawlik - UNCW

Sponges are dominant animals on Florida coral reefs, and perform many important ecological functions. The giant barrel sponge, *Xestospongia muta*, is common on deeper reefs. The largest individuals are more than 2000 years old.

One very prominent sponge on Florida reefs is the giant barrel sponge, *Xestospongia muta*, which is common at depths greater than 10 meters (33 feet). Between 2000 – 2006, populations of *X. muta* on Conch Reef off Key Largo grew by 46%, possibly in response to more free space as the populations of reef-building corals declined. Growth estimates indicate that the very largest individuals of this species are over 2000 years old. These large, long-lived sponges have been called the "redwoods of the reef."

J. Pawlik- UNCW

A large barrel sponge on Conch Reef, estimated to be 150-years old, contracted Sponge Orange Band syndrome and died only a few weeks after the syndrome was first observed.

Sponges currently face several threats. For example, an increase in human activities on the reef has resulted in an increase of abandoned rope and fishing line that, when dragged by storm currents, slice cleanly through the base of sponges, leaving them unattached, often rolling on the seafloor. More troubling is a newly described pathogenic syndrome, Sponge Orange Band, that rapidly travels through the tissues of large barrel sponges and kills them. Many more years of monitoring are required to determine the long-term responses of sponge populations to these new threats.

A vibrant sponge fishery existed in south Florida

Billy D. Causey, John Stevely, and Don Sweat

Sponges are one of the simplest forms of multicellular animals. There are over 9000 species of sponges worldwide. They are hollow and their interior walls are lined with small pores that allow water to flow through the sponge. Their cells capture microorganisms, such as algae and bacteria for food. They are able to reproduce by budding, which means that a new sponge can grow from a small piece that is broken off.

Commercially important sponges have a protein-like substance called "spongin" in their cells. Spongin is similar in structure to hair and allows dried sponges to be durable, soft, and absorb water.

Until the mid-19th century, the world sponge supply came from the Mediterranean Sea. But, suitable sponges were found at that time in Florida and the Caribbean and sponge fisheries were quickly established in Florida, Cuba, and the Bahamas. By 1890, a fleet of 500 vessels was engaged in sponging in Florida and catches were stored in "crawls" that dotted inlets and coves from Miami to Key West. Most sponges were sold in Key West, and sponging netted Monroe County almost one million dollars annually.

Sponging was important to the economy of other areas of Florida, including Tampa, Cedar Key, Carrabelle, and Apalachicola. In 1879, Carrabelle had the largest sponge fleet in Florida next to Key West. Around 1900, Tarpon Springs replaced Key West as the sponge capital of Florida, but sponge auctions were held continuously in Key West until 1947. Prior to World War II, Florida produced about 270,000 kilograms (600,000 pounds) of sponges annually. Red tides, overfishing in the late 1930s, and introduction of synthetic sponges during the 1950s shrunk the fishery to a small fraction of its former importance. In recent years, the Florida production has been about 27,000 kg (60,000 lbs) annually.


NOAA

A sponge auction in Florida, ca. 1900.

Commercial sponges are not found on coral reefs, but are found on the hardbottom community. In the Florida Keys, commercial sponges represent about 2% of the sponge community, and they are harvested from small boats by hooking. Fishermen use a long pole to tear (hook) the sponge from the bottom. Research has shown that if sufficient sponge tissue is left attached to the bottom, about a third of the sponges survive and regenerate. In addition to leaving enough sponge tissue to encourage regeneration, other current fisheries management measures include a minimum size of 12.7 centimeters (5 inches), a prohibition on diving for sponges in the Florida Keys, and establishment of sponge sanctuaries in Everglades and Biscayne National Parks.

Sponges are remarkable "pumping machines" and can pump about 10,000 times their own volume in water during 1 day. Because they remove bacteria and other particulate matter from the water, many believe that sponges help maintain clear water conditions in areas where they are found. Recent research has shown that the current harvesting level in the Florida Keys has a negligible impact on benthic community structure and water quality.

Wading bird populations in south Florida have significantly declined

Erin Woods, Adam Chasey, Mac Stone, and Jerome J. Lorenz

The wading bird populations of south Florida in the 1830s are estimated to have been approximately 2.5 million birds. By the turn of the century, however, the demands of the fashion industry for feathers, combined with environmental degradation, resulted in a population loss of more than 80%.

M. Stone

Large wading bird rookeries were once much more common throughout south Florida.

In the early 1900s, wading birds with elaborate plumes were hunted nearly to extinction in order to adorn the hats of American and European women. Birds such as the flamingo, roseate spoonbill, snowy egret, and the reddish egret were heavily targeted. Despite legislation outlawing plume hunting in 1901, poaching and black market sales continued to devastate bird populations. According to ornithologist W.E.D. Scott, a wading bird pelt sold for up to 1 dollar, while a spoonbill pelt could sell for 5 dollars. Finally, a grassroots awareness campaign in 1910 made the fashion socially unacceptable. Without economic incentives, the hunting trade died off and bird populations began to slowly recover.

Bird populations in south Florida continued to increase into the 1930s, up to an estimated 245,000 nesting individuals. Their numbers showed signs of a promising recovery amidst a "transitional" time in Florida. However, south Florida underwent drastic ecological changes with the partial drainage of the Everglades and the completion of the Tamiami Trail in 1928. Diverting natural freshwater flow patterns permanently changed the hydrology of south Florida. The once inundated marshes became arable land suitable for agriculture, cattle ranching, and housing communities. The coastal Everglades experienced higher salinity concentrations due to reduced freshwater inputs, which devastated fish and plant populations. Because of these changes, wading birds largely abandoned nesting in coastal estuaries and now nest mainly in the managed Water Conservation Areas located north of Everglades National Park.

Concurrent with this spacial shift was a change in community structure from tactile feeding birds (e.g., wood storks, white ibis, roseate spoonbills) to visual predators (e.g., egrets, herons). These changes indicate that the once highly productive estuaries became so degraded by water management practices that they could not support the huge numbers of waders that once nested there. Between early drainage years (1930s) and late drainage years (1970s – 1980s) the total nesting population declined by 93%.

Throughout the past century, wading bird populations have shown a remarkable resilience despite overhunting and habitat destruction. Legislation and social solidarity once provided the framework to revive one of the most biodiverse regions in North America and brought forth a marked recovery of wading birds. History has shown that striking the balance between societal and environmental needs is not only imperative, but above all, it is achievable. Wise ecosystem management is required for the recovery of wading bird populations of south Florida.

You can help to protect south Florida birds

Karen Dyer, Michelle Robinson, and Jerome J. Lorenz

Birds are an important and highly visible component of the natural world. They serve many critical roles in nature, including seed dispersal, pollination of flowering plants, and insect and rodent control. Additionally, birds are important indicators of environmental health. As encounters between humans and wildlife become more frequent, many people wonder what they as individuals can do to help our native birds.

Each year, tens of millions of songbirds, including warblers, vireos, and thrushes, pass through the state of Florida on their annual migrations between wintering and breeding grounds. Many of these small birds make long flights over open water, relying on south Florida as a stopover point for replenishing vital energy reserves. As the Florida landscape becomes more fragmented, these birds must rely on isolated patches of suitable habitat for foraging and shelter. Individuals can help by planting native trees and shrubs, which provide high quality food and cover for birds. Additionally, leaving dead trees standing provides a site for cavity-nesting birds to raise their young.

The extensive coastline of Florida provides refuge for many species of terns, gulls, and shorebirds. Many of these birds nest on the ground, placing their inconspicuous eggs in shallow scrapes in the sand. In order to avoid disturbing or damaging nests, refrain from driving on beaches, especially during the nesting season, and obey all signs marking sensitive areas.

M. Stone

Prothonotary warblers winter in Central America and typically nest in cypress swamps.

What can you do?

- Obey all posted signs in natural areas.
- Remove and recycle all fishing line.
- Plant native vegetation in your yard.
- Place a bell on the collar of your cat.
- Limit your use of pesticides and other chemicals.
- While at the beach, keep your dogs on a leash when birds are nesting.
- Leave dead trees standing and install nest boxes for cavity-nesting birds.
- Keep bird feeders away from windows to avoid collisions.
- Dispose of all trash properly.

South Florida is home to a variety of species of wading birds, including herons, egrets, and spoonbills. Wading birds often nest in large rookeries, where hundreds of nests can be found on a single island. Boat traffic in close proximity to these rookeries can cause a significant amount of disturbance to nesting birds. When adults are flushed from their nests, their chicks are left vulnerable to predation, inclement weather, and sun exposure. Avoid approaching nests, especially when operating a motorboat, and always obey signs designating "No Wake" and "No Entry" zones. It is also extremely important to properly dispose of all monofilament fishing line and plastics that can entangle birds, putting them at risk of strangulation, dehydration, and eventual death.

Development and alteration of natural habitats continues to threaten the diverse bird life of Florida. There are, however, many things that individuals can do to ensure the welfare of our native birds. With minimal effort, we can effect positive change and ensure a brighter future for all of our wildlife.

The roseate spoonbill is an indicator of ecosystem condition

Karen Dyer and Jerome J. Lorenz

Not everything within an ecosystem can be monitored. Complex community structure makes it necessary for scientists to select environmental indicators that are characteristic of the entire system. Within the Everglades, the roseate spoonbill (*Platalea ajaja*) serves as an "umbrella" indicator, representing the overall health of the ecosystem.

M. Stone

Roseate spoonbills and shorebirds forage at Lake Ingraham in Everglades National Park.

During the dry season, low water levels force large numbers of small demersal fishes into remaining wetland areas. Many top predators, including crocodilians, game fish, and wading birds, take advantage of this concentration of prey to forage efficiently. Tactile feeding wading birds such as the roseate spoonbill are especially dependent on these high prey densities. Spoonbills time their nesting to coincide with the dry season so that there is a reliable food source to meet the energetic needs of their rapidly growing young.

M. Stone

American crocodiles require many of the same physical and biological conditions as roseate spoonbills.

Roseate spoonbills were largely extirpated from Florida during the plume hunting era around the turn of the century. By the late 1970s, however, there was again a large nesting population in Florida Bay. In the early 1980s, a series of canals and water control structures were built upstream from where the majority of the spoonbills were nesting at that time. This canal system dramatically modified the quantity and timing of freshwater reaching the coastal mangrove wetlands where the spoonbills primarily foraged, resulting in increased salinities and fewer wetland fishes.

B. Mulrooney courtesy of NPS

Spoonbills require close access to abundant prey in order to successfully fledge their young. Spoonbills time their nesting with the dry season when prey is concentrated in small pools.

Research performed by Audubon scientists in Florida Bay since the 1930s has shown that changes in spoonbill nesting distribution, and concurrent declines in reproductive success, can be directly attributed to these alterations in water deliveries. The return of the Everglades to more historical hydrologic conditions is expected to reverse this trend. Recovery of roseate spoonbill populations in the Everglades would indicate successful restoration for the entire system.

The pink shrimp life cycle connects Dry Tortugas with Florida Bay

Joan Browder

The pink shrimp, *Farfantepenaeus duorarum*, is found in coastal waters and estuaries from Chesapeake Bay south through the Florida Straits and the Gulf of Mexico to the tip of the Yucatán Peninsula. It is one of the most ecologically and economically important animals in the south Florida marine ecosystem and is the target species of a major fishery operating near the Dry Tortugas.

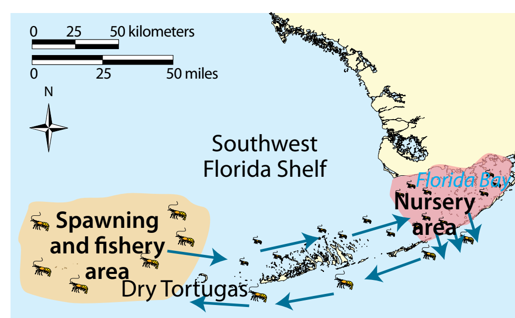
The pink shrimp is an opportunistic omnivore that consumes copepods, small mollusks, marine worms, benthic diatoms, blue-green algae, filamentous green algae, detritus of vascular plants, bacteria films, slime molds, and yeasts. Shrimp "convert" those small items into a food source that is substantive enough for larger animals to eat. Pink shrimp are prominent in the diet of many higher trophic level animals, from wading birds to highly sought after fish species, such as gray snapper, spotted sea trout, and red drum.

T.L. Jackson - NMFS

The pink shrimp is an ecologically and economically important animal in south Florida.

Pink shrimp become sexually mature in about 1 year and have been reported to live up to 3 years. In south Florida, adult pink shrimp spawn near the Dry Tortugas, near the edge of the Southwest Florida Shelf. Fertilized eggs and larvae are planktonic. From the perspective of such a small, newly hatched animal, it is a long way from the Tortugas spawning grounds to nursery grounds in Florida Bay (about 113 kilometers [70 miles]); however, many individuals of a spawning cohort complete the voyage, undergoing the transformation from protolarvae, mysis stage, and postlarvae along the way.

The entry of pink shrimp postlarvae into Florida Bay is from the west, across the lower Southwest Florida Shelf. Pink shrimp, like other shrimp species and blue crabs, use a selective tidal transport: they move up in the water column to travel shoreward with the faster moving surface currents, and down in the water column to avoid being carried backward by outgoing tides. The voyage across a continental shelf to reach Florida Bay nursery grounds may be unique to Tortugas pink shrimp because this distance of travel has not been reported for pink shrimp elsewhere in their geographic range.



Adapted from M. Criales - NMFS

Scientists have been studying pink shrimp migrations since about 1960. Adult pink shrimp spawn around the Dry Tortugas, near the edge of the Southwest Florida Shelf. Fertilized eggs and small, newly hatched animals travel approximately 113 km (70 mi) to their nursery grounds in Florida Bay. Juvenile shrimp feed and grow in the seagrass meadows of Florida Bay and then move out to the Atlantic Ocean through tidal passes between the Florida Keys island chain. The movement of the Tortugas pink shrimp may be unique because no other pink shrimp in the geographic range of the species have been reported to make such a long-distance journey from egg to adulthood.

Juvenile shrimp feed and grow in the seagrass meadows in Florida Bay and they depart the Bay as young adults by many routes, including through the tidal passes between the Florida Keys. Residents and tourists of the Keys intercept the hordes of migrating shrimp with nets from bridges and boats. The young adult shrimp that get through the gauntlet of nets, as well as those that leave the Bay by other directions (e.g., west, southwest), end on the Tortugas spawning grounds where they can be captured by shrimp trawls.

NOAA

Pink shrimp are caught by shrimp boats pulling trawl nets at the spawning grounds in the Dry Tortugas.

While many shrimp are caught soon after their arrival in the Tortugas, some survive to spawn and some live to grow much larger. Besides the Tortugas fishery, there are smaller food and bait shrimp fisheries, notably along the Bay side of the Upper Keys and in Biscayne Bay. Western Florida Bay is the main nursery ground for pink shrimp in south Florida, and judging from the density of juvenile pink shrimp, other parts of Florida Bay are less important nursery grounds. Nearby nursery grounds outside Florida Bay include Whitewater Bay and Biscayne Bay.

Scientists have been studying pink shrimp on their south Florida nursery grounds since at least the 1960s, and almost from the beginning of the studies scientists worried about the effects of upstream water management on the survival and growth of young pink shrimp in the estuaries. Later studies found statistical relationships between pink shrimp production on the Tortugas spawning grounds and indices of water flow from the Everglades. A computer model was developed that simulated growth, survival, and potential harvests of juvenile pink shrimp as a function of salinity and temperature, based on laboratory trials subjecting small pink shrimp from Florida Bay to a range of salinity and temperature combinations. The model suggested that pink shrimp have a broad tolerance range, but both extreme low salinity and extreme high salinity were unfavorable. Therefore, survival and growth may be suppressed in Florida Bay during periods when salinity exceeds 45 – 50 parts per thousand, which has often been the case in parts of Florida Bay in recent years.

Perhaps because the pink shrimp has been relatively well studied in south Florida and a relationship with salinity has been suggested, this species was chosen for use as an ecological indicator to help assess the effect of water management changes associated with the Comprehensive Everglades Restoration Plan on south Florida estuaries. The fact that the pink shrimp is abundant, widespread, and economically as well as ecologically important, also weighed in favor of its selection as an indicator species. The relatively long time series of data on both juvenile densities in Florida Bay and adults in the fishery make the species especially valuable as an indicator.

The life history of the pink shrimp demonstrates the importance of connectivity of multiple habitats on the growth and survival of a species. It is important to note that the shrimp harvest declined to record lows during the period of most intense seagrass die-off in Florida Bay. The requirement of multiple habitats to complete their life cycle makes pink shrimp, and other species with similar requirements, vulnerable to multiple stresses. Because pink shrimp are such an important link in marine food chains, overharvesting at their spawning grounds has the potential to alter the balance of the entire south Florida ecosystem. Important nursery grounds, including estuaries and coastal seagrass communities, must be protected from impacts of development and pollution to maintain this important species.

Stone crabs are an important fishery in south Florida

Anne McMillen-Jackson and Theresa M. Bert

Stone crabs are territorial, carnivorous, and cannibalistic predators. One look at their claws, which are massive in proportion to their body size, verifies this observation. In the United States, stone crabs range from North Carolina through Texas. The Florida stone crab, *Mennippe mercenaria*, is most common in the southeastern Atlantic Ocean and throughout pennisular Florida. The Gulf stone crab, *Mennippe adina*, occurs principally in the northern and western Gulf of Mexico.

FWRI

Two stone crab species occur in Florida waters, Florida stone crab (left), and the Gulf stone crab (right).

The Florida stone crab inhabits mixed seagrass-hardbottom habitat. Juvenile stone crabs usually do not dig burrows, but hide among rocks, sponges, soft corals, and other benthic biota. Adult crabs dig burrows under seagrasses or excavate holes in the emerged rocks on the seafloor. The Gulf stone crab also occupies those habitats, but prefers muddier bottoms and oyster reefs. Both species feed primarily on mollusks, including scallops, clams, conchs, and oysters, which they crush with their powerful claws. They occasionally feed on recently dead animals. Predators that feed on stone crabs include octopus and humans.

Stone crabs can live 7 – 8 years and reach sexual maturity in 2 years for males or 3 years for females. The breeding season is from spring through fall. Mating occurs after the female molts and her exoskeleton (i.e., shell) is soft. The male crab takes the female into his burrow and stays with her until she molts, and then mates with her. After mating, male and female crabs go their separate ways.

FWRI

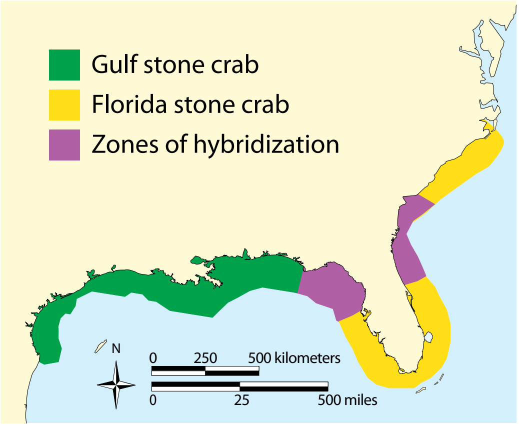
Female stone crab with newly released eggs. As eggs mature, they turn from orange to gray.

The female crab holds the sperm in a special organ on her underside until her eggs are ready to release. She simultaneously releases the eggs with the sperm and holds the fertilized eggs on her abdomen until they hatch. The eggs are orange in color when they are first released and turn darker as they develop. Eggs hatch as larvae that are planktonic and go through six stages while suspended in open waters. After about a month in the planktonic stage, they settle as juvenile crabs. Female stone crabs can spawn four to six times each season.

Florida and Gulf stone crabs can interbreed to produce hybrids that have different coloration and body patterns than either parent. Hybrids can be intermediate between the two species in coloration, or they can have unique colors and patterns. They can also have strange mottling or blotching on their carapaces or claws.

What does the future hold?

Will the hybrid zones expand until all stone crabs are genetically similar enough to call one species, or will the different habitats keep most of the pure species within their current ranges? Only time will tell.



Distribution of the Florida stone crab, the Gulf stone crab, and the hybrid between the two species.

The stone crab fishery is unique in that only the claws are harvested and the crab is returned to the water. This is possible because stone crabs can undergo autotomy and regeneration. Autotomy is the ability to self amputate an appendage. This is a defense mechanism that allows a crab to "drop" a claw or leg that has been grasped by a predator, or in a fight with another stone crab, helping it escape. The next time the crab molts, it regenerates, or regrows the limb and expands the claw in size before the shell hardens. It takes approximately 24 months for a regenerated claw to reach harvestable size.


FWRI

A regenerating claw of a stone crab. After the crab molts, the claw will expand in size before the shell hardens.

When harvesting claws, it is important to break the claw off in the correct manner. A good break occurs along a fracture plane and allows the crab to regrow the limb without loss of blood. This increases the probability of crab survival and regeneration. A bad break will result in cracking the crab shell, causing loss of blood and an increased probability of death.

Nearly 15% of commercially harvested crab claws have been regenerated, indicating that crabs survived the declawing process. Regenerated claws can be distinguished from original claws by the appearance of bumps on the inside surface of the claw. In an original claw, the pattern is composed of multiple lines that resemble a fingerprint. In a regenerated claw, the pattern appears as broken lines or dots.

Stone crabs are commercially harvested almost exclusively in Florida, and principally in southwestern Florida. Florida regulations require a claw size of 7 centimeters (2.75 inches), as measured from the tip of the immovable part of the pincher to the first joint. Nearly all females have had at least 1 year to reproduce before they have a claw of that size. However, because males have proportionally larger claws, and because mating in males is size-dominant, many males may either not have reached reproductive size or had an opportunity to mate before their claws are harvested. Thus, current Florida law achieves the goal of protecting the female crabs before reproduction, but does not achieve that goal for males.

From 2006 – 2010, commercial stone crab landings have averaged about 1.4 million kilograms (3 million pounds) of claws, with an average annual dockside value of about $22 million. There are no estimates of the size of the recreational fishery. The number of crab traps in the Florida fishery has tripled since 1989 – 1990 and the level of landings has been low and declining since that time.

Interesting facts

- Stone crabs are usually right handed.
- The large crusher claw can exert over 6350 kg (14,000 lbs) per square inch of force.
- Males live to about 7 years and females live to about 8 years.

Animal Diversity

The life cycle of the Caribbean spiny lobster includes multiple larval and juvenile stages

Carrollyn Cox

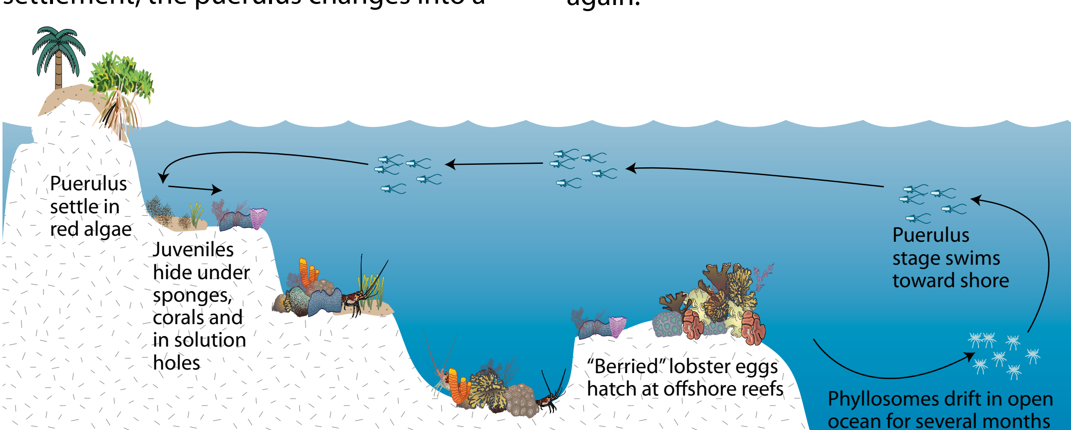
The Caribbean spiny lobster has a complex life history. The main reproductive period is from March – August. During mating, male lobsters deposit a sperm packet on the abdomen of females. When a female releases eggs, she scratches the sperm packet, releasing the sperm that fertilize the eggs. Egg-bearing or "berried" lobsters carry eggs under their tail for about 3 weeks. An average-sized adult female may have from 250,000 – 2,000,000 eggs per clutch and may have 1 – 3 clutches per reproductive season. Larger females produce more eggs than younger, smaller female lobsters.

As eggs mature, they turn from orange to brownish orange and the female migrates to the fore reef, where eggs hatch. Eggs hatch to tiny flat-shaped larvae called phyllosomes that are quite transparent, except for their eyes, which are pigmented. Phyllosomes are carried by ocean currents and can travel for hundreds of miles as plankton in the open ocean. Phyllosome larvae pass through 11 developmental stages before changing into a postlarval settlement stage called a puerulus. The puerulus is a clear, nonfeeding stage that actively swims and settles in shallow nearshore areas. After settlement, the puerulus changes into a juvenile that looks like a miniature adult lobster.

Young juvenile lobsters live alone, primarily in clumps of algae or in seagrass. They feed on small snails and crabs. After a few months, juveniles move to hardbottom habitat and find shelter under sponges and corals and in solution holes and crevices. They usually shelter with other lobsters in "dens." It takes about 2 years for lobsters to reach reproductive maturity and start the life cycle over again.

Fact or fiction?

There is a common myth that adult spiny lobsters may travel by way of the deep ocean from one country to another. However, the extremely cold temperatures of the deep ocean prevent this from occurring. Spiny lobsters are rarely found below a depth of 90 meters (300 feet). Spiny lobsters become sluggish in temperatures below 16°C (60°F) and prolonged exposure to temperatures below 10°C (50°F) will lead to death. Even in the warm Caribbean Sea, temperatures in the deep areas easily dip below 4°C (40°F), which prevents adult lobsters from crossing deep waters.



Life cycle of the Caribbean spiny lobster.

Left: egg-bearing female; Top right: eggs; Bottom right: phyllosome.

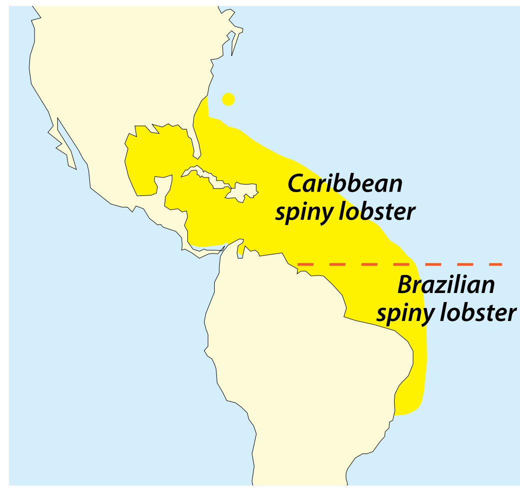
Top left: puerulus; Bottom left: juvenile lobster; Right: mating lobsters.

The Caribbean spiny lobster is found from the Carolinas to Brazil

Dave Eaken

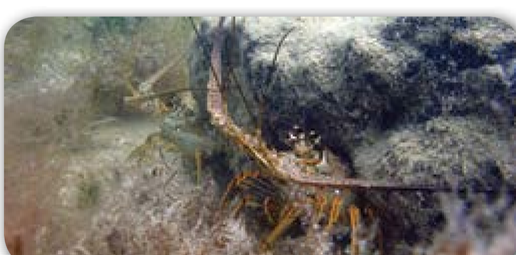
Panulirus argus occurs in two distinct forms, a Caribbean subspecies (*Panulirus argus argus*) and a Brazilian subspecies (*Panulirus argus westonii*). As its common name suggests, the geographic range of the Caribbean spiny lobster is primarily the Caribbean Sea. However, the Caribbean spiny lobster also occurs in the Gulf of Mexico and the western Atlantic Ocean as far north as the Carolinas, east to Bermuda, and as far south as northern Brazil. The Brazilian form occurs on the coast of Brazil and occasionally elsewhere.

It was once thought that the two subspecies were geographically isolated from each other because runoff from the Amazon River and Orinoco River basins extends far out into the Atlantic Ocean and acts as a barrier to larval migration. Genetic fingerprinting of the two subspecies has confirmed that they are genetically distinct. However, the Brazilian form of *P. argus* is occasionally caught in Florida. How can that happen?



M.J. Butler IV - ODU

Distribution of the Caribbean spiny lobster and the Brazilian spiny lobster. Orange dashed line marks the boundary where the Caribbean spiny lobster overlaps with the Brazilian spiny lobster.



R.D. Bertlesen - FWC

Subadult spiny lobsters among algae and sponges.

Larval wanderings

The phyllosome larvae of both Caribbean and Brazilian forms of *P. argus* normally spend 5 – 9 months in the open ocean. During this long larval stage, they may travel hundreds, or even thousands, of miles on fast-moving ocean currents. It seems that occasionally phyllosomes are able to ride those currents from Brazil to Florida, transform into puerulus postlarvae, and settled in Florida waters where they grow to adults. Puerulus postlarvae actively swim and use chemical cues, lunar phase, and perhaps temperature to guide them in their long swim from the open ocean to shallow nearshore waters. Thus, the barrier is not perfect and there is some overlap of these two subspecies of *P. argus*.

The same ocean currents responsible for the robust transport of larvae may also sweep them past suitable settlement habitat, such as into the northern latitudes of the mid-Atlantic Ocean and beyond, where these early stage lobsters will perish.

Limitations to adult movement

Although the free-floating larvae may travel across miles of open ocean from one country to another, adult populations of spiny lobsters are considered geographically isolated within their population. Adult lobsters are highly mobile, sometimes traveling up to 3.2 kilometers (2 miles) per day; however, where they can travel is limited by depth and temperature.

Caribbean spiny lobster larvae are widely dispersed

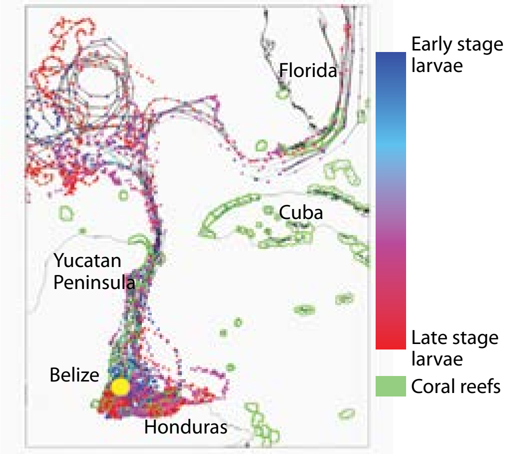
Mark J. Butler IV

Like many other marine animals, Caribbean spiny lobsters produce tens to hundreds of thousands of tiny eggs in a single clutch. Those eggs hatch into miniscule larvae that are cast into the open sea where they dwell for several months. Although extraordinarily numerous at birth, the chance that any one larvae will survive its planktonic journey is less than 1 in 10,000. Those lucky enough to survive months at sea can also potentially drift thousands of miles from their birth site.

The phyllosome stage larvae of Caribbean spiny lobsters drift in ocean currents for many months.

No one really knows where the postlarvae that enter Florida waters began their oceanic journey or where the female lobsters that spawned the next generation of lobsters in Florida actually live. The answer to this question, so critical for fishery management, is more elusive than one might expect. For years it was thought that the Caribbean Sea was like a giant mixing bowl where long-lived larvae spawned at any one location were dispersed to all others. However, recently discovered genetic techniques have exposed subtle genetic differences in lobsters among regions, suggesting that larval dispersal is more limited than previously supposed.

Support for limited dispersal of larvae comes from studies that use high-powered computer models that couple ocean currents and larval biology to predict larval dispersal. Changes in larval behavior that move them to different depths in the sea, both daily and at different stages in larval development, appear to play an important role in constraining larval dispersal. So much so, it is thought that in many locales lobster larvae remain within a few hundred miles of their spawning site rather than dispersing hundreds to thousands of miles away. However, in areas such as the Mexican Yucatán Peninsula and the Florida Keys, where offshore currents are strong and unidirectional, and eddy currents are short-lived relative to the long larval period of lobsters, it is improbable that lobster larvae return to where they were spawned. So, the answer to the question "Where do Florida spiny lobster come from?" can not yet be answered with precision. The best scientific evidence suggests that few larvae may come from Florida and most larvae come from the southern and western Caribbean.



Example of larval spiny lobster dispersal from a spawning location at Glover's Atoll in Belize (yellow dot) in June 2004 as predicted from a computer simulation model. Colored dots indicate the position of simulated larvae at different times during their development, from shortly after hatch (blue) to the end of their 6-month larval period (red). Green margins show the approximate locations of coral reefs. In this simulation, most larvae are retained in an eddy system between Belize and Honduras, whereas other are swept north, away from the Yucatán Peninsula and into south Florida by strong unidirectional currents. (Figure generated using MATLAB®, modeling courtesy of Claire B. Paris, University of Miami).

Caribbean spiny lobsters require healthy nursery habitats

Mark J. Butler IV

At different life stages the spiny lobster lives in distinctly different habitats. The puerulus postlarval stage selects hardbottom habitats for shelter using chemical cues to locate and preferentially settle in clumps of red macroalgae. Red macroalgae is common on shallow hardbottom habitats on the Gulf side of the Florida Keys.

Some postlarvae settle in seagrass meadows or on submerged mangrove roots with heavy growth of algae and sponges, but hardbottom areas are by far the most important nursery habitat for lobsters in south Florida. In fact, the south Florida lobster population is limited by the supply of postlarvae and the amount of healthy hardbottom habitat.

Once settled in nursery habitat, the postlarvae change into algal-dwelling juveniles, and after a few months, emerge from the algae to become postalgal-dwelling juveniles. Postalgal juveniles become social and take daytime refuge in crevices and solution holes and under corals and sponges in hardbottom habitat. Threats to juvenile lobsters and their nursery habitat include poaching, disease, hurricanes, climate change, and diminished water quality. The hardbottom nursery habitat for postlarvae and juveniles is particularly sensitive to changes in water quality conditions. Large sponges, such as loggerhead sponges and vase sponges, are the primary shelters for young lobsters in south Florida. Periodic die-offs of large sponges have been documented in south Florida since the mid 1800s. In the early 1990s, and again in late 2007, sponges over large areas of Florida Bay and the Florida Keys died. Scientists believe that the sponge death was due to their feeding tubes being blocked by tiny algal cells that are common in planktonic algal blooms in Florida Bay.

Scientists believe that the devastation of hardbottom nursery habitat is the result of a "cascade" of disturbances and is an example of the intricate, and

M.J. Butler IV - ODU

Postlarval lobsters arrive inshore at night on rising tides near new and full moons and are attracted to the chemical scent of large clumps of red algae found on hardbottom habitats.

R.D. Bertelsen - FWC

Loggerhead sponges are common in south Florida shallow hardbottom habitats. They filter plankton from the water column and provide critical shelter for numerous organisms, including juvenile spiny lobsters.

M.J. Butler IV - ODU

In the early 1990s, sponges over large areas of the Florida Keys died in response to persistent algal blooms. Skeletons of sponges were all that were left, leaving little shelter in this nursery habitat for lobsters.

often unknown, interconnectedness of ecosystems. Rapid changes occurred in Florida Bay following several years of drought in south Florida and the historical alteration of natural freshwater flow to the Everglades. Starting in 1987, thousands of acres of seagrasses rapidly disappeared. Although the precise causes may still be debated, causal factors include eutrophication leading to overdevelopment of seagrass beds, stress due to chronic hypersalinity, and abnormally warm late summer and fall temperatures. In 1991, a series of dense phytoplankton blooms developed, sparked by nutrients released from dying seagrass and exposed sediments. The blooms persisted for months and continue today. The common bloom organism is a blue-green cyanobacteria that is lethal to sponges in high concentrations. Juvenile lobsters that depend on large sponges for shelter declined more than 30% in areas impacted by sponge die-off.

The large-scale seagrass die-off and algal blooms helped to energize the public and resource managers to initiate what has become the largest ecosystem restoration project on the planet—the Comprehensive Everglades Restoration Plan. The goal of the plan is to restore the greater Everglades ecosystem, including "The River of Grass" and adjacent marine areas. Because water is the key to restoring the ecosystem, one of the major goals of the initiative is "getting the water right." Improving the quality, quantity, timing, and distribution of water delivered to the Everglades and Florida Bay is essential for sustaining and restoring the south Florida ecosystem. Currently, pollutants such as nutrients, metals, and other contaminants have diminished the quality of water in the ecosystem and harmed plants, fish, and other wildlife. To achieve and sustain restoration of this ecosystem, water needs to be clean and unimpaired by excess nutrients. It is hoped that successful implementation of restoration plan will help restore the healthy conditions of the hardbottom nursery habitats that lobsters in south Florida are dependent upon. Details of Comprehensive Everglades Restoration Plan can be found at: http://www.evergladesplan.org

M.J. Butler IV - ODU

Juvenile lobsters live within red algae clumps, where they find abundant small prey and are camouflaged from predators.

Caribbean spiny lobsters are both predators and prey

Adrianna Zito

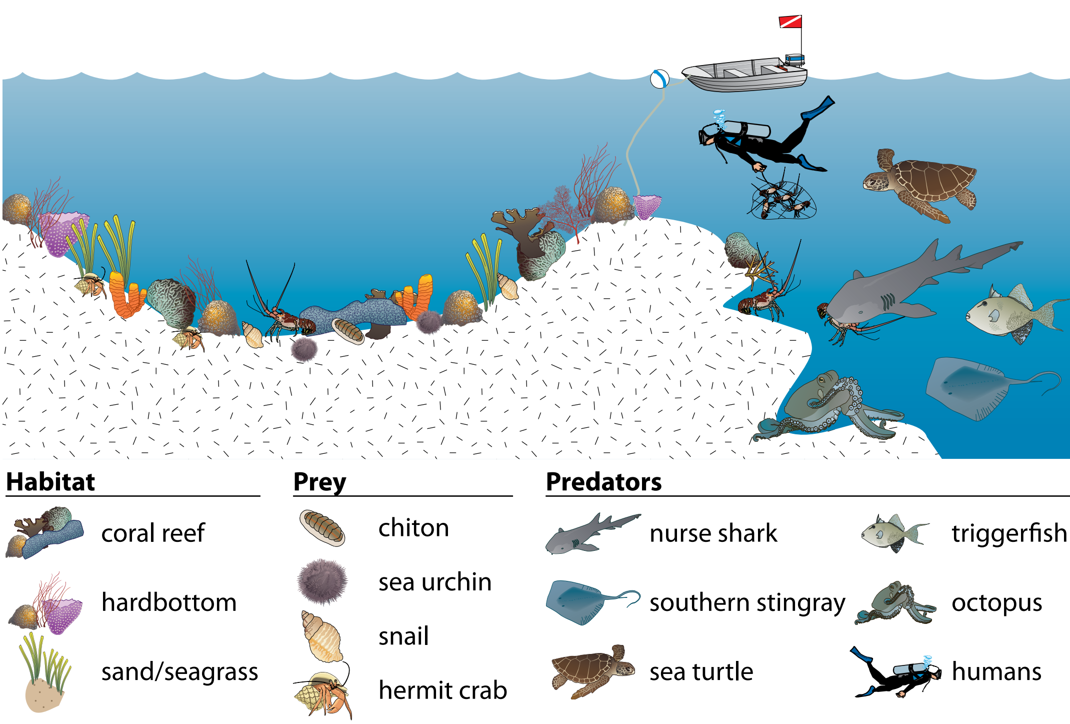
Spiny lobsters are an important part of the south Florida marine ecosystem as both predators and as prey. Lobsters hide from predators in crevice shelters during the day and actively forage at night. The size and composition of lobster predators and prey vary between habitats and throughout the lobster life history.

Lobster predators

A diverse group of motile marine predators are known to prey on adult lobsters. The majority of the predators are fish, including triggerfish, grouper, snapper, nurse sharks, moray eels, and stingrays. Other common predators are loggerhead sea turtles, octopuses, blue crabs, and humans.

Lobster prey

Lobsters are opportunistic predators, feeding on abundant prey organisms that vary with habitat. Typical prey items are slow-moving, marine invertebrates with calcareous shells or exoskeletons, such as chitons, sea urchins, hermit crabs, and snails. Lobsters have strong mandibles that enable them to break open the protective coverings of prey. The calcium they ingest from prey items is used to build their own strong exoskeleton.



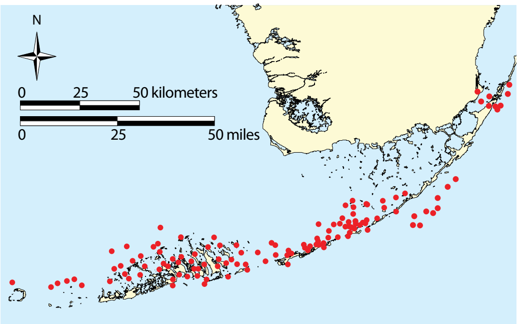
Caribbean spiny lobsters are a key component of the marine ecosystem in south Florida as both predators and prey.

Juvenile Caribbean spiny lobsters are plagued by a lethal viral pathogen

Donald C. Behringer, Mark J. Butler IV, and Jeffrey D. Shields

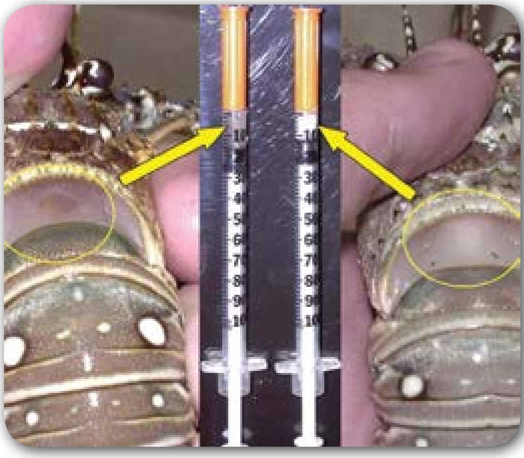
Discovery of PaV1

Panulirus argus Virus 1 (PaV1) was discovered in 1999 in juvenile lobsters in the Florida Keys, and mainly affects sublegal-sized lobsters. It is the first naturally occurring pathogenic virus reported from lobsters anywhere in the world. Although the origin and time of emergence of PaV1 are still being investigated, it is known that it is a DNA virus that replicates entirely within the nucleus of the cells it infects. In the later stages of the disease, lobsters become lethargic, and their normally clear blood becomes chalky white. The virus kills lobsters within one to several months after infection.



Location of lobster sampling stations for PaV1 virus in 2002.

In yearly surveys conducted from 2000 – 2009 at 12 sites in the Middle and Lower Keys, the prevalence of this disease at some sites has been as high as 50%, but has an overall prevalence of 5% – 8%. It is most common among the smallest of juvenile lobsters (less than 15%) and declines in prevalence with increasing size. In 2002, a comprehensive survey of 120 hardbottom sites from Key Largo to the Marquesas found an overall prevalence of 5%. PaV1 is not limited to the Florida Keys. Confirmed infections have been found in St. Croix, Mexico, and Belize.



D.C. Behringer - UF

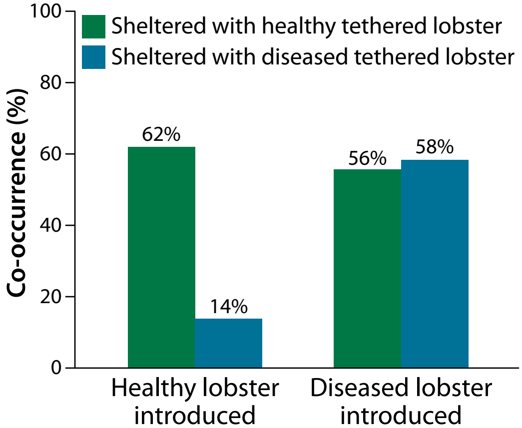
Blood of healthy lobsters is clear (left) and blood of infected lobsters is chalky white (right).

Effects on social behavior and disease dynamics

Caribbean spiny lobsters are highly social and are typically found aggregated under structures. However, infected lobsters are typically found alone (94%), whereas healthy lobsters often co-occupy dens (only 46% solitary). In laboratory experiments, normally social healthy individuals avoided cohabitation with diseased lobsters. Remarkably, this disparity in aggregative behavior was driven by changes in the behavior of healthy lobsters, not the diseased lobsters, a result not reported before. Healthy animals appear to have the ability to identify and then avoid diseased animals before they become infected.

2002 Keys-wide PaV1 Survey	
Total sites surveyed	120
Sites with lobsters	60
Sites with PaV1	60
Overall prevalence	5%

The presence of PaV1 is widely distributed through the Florida Keys. Out of 120 sites surveyed in 2002, the virus was present in all 60 sites with lobsters.



Adapted from Behringer, Butler IV, Shields (2006)

Results of laboratory shelter selection experiment. Noninfected and visibly infected juvenile lobsters were given a choice of sheltering alone or with another lobster, either infected or not. Most healthy lobsters chose to shelter with a healthy lobster (62%) and avoided the infected lobster (14%).

Transmission and alternate hosts

Potential modes of transmission for PaV1 include contact, ingestion, and waterborne transmission. Of the modes investigated, ingestion was the most efficient, but contact and waterborne transmission were also viable modes. Waterborne transmission up to 1.8 meters (6 feet) was demonstrated in the laboratory, but only for the smallest juveniles. Sixty-five percent of the exposed small juveniles became infected. The ease of transmission to the smallest lobsters partially explains the high disease prevalence observed in the field.

Stone crabs (*Menippe mercenaria*), spider crabs (*Mithrax spinosissimus*), and spotted lobsters (*Panulirus guttatus*) reside in shelters with spiny lobsters, or use similar habitats. Those species were exposed to PaV1 in the laboratory by inoculating them with blood from an infected lobster. None of the spotted lobsters (30 individuals), stone crabs (30), or spider crabs (20) were found to have contracted the PaV1 infection. Therefore, PaV1 virus appears highly specific to Caribbean spiny lobsters. However, there are many potential hosts that have not been tested and the potential for "carriers" or other reservoirs of infection may also exist. The effect of ingesting an infected lobster on human health is unknown, but unlikely; none of the researchers working with this viral disease have acquired the infection.

Conclusions

Numerous advances have been made in understanding the ecology and epidemiology of the PaV1 disease since its discovery. Studies have found that: 1) PaV1 is lethal; 2) Infection is largely limited to juveniles; 3) Infection is potentially reduced by the ability of healthy lobsters to avoid infected ones; and 4) PaV1 appears highly specific to the Caribbean spiny lobster. Current research indicates avoidance is driven by the chemical scent of diseased lobsters. High prevalence in small lobsters and rampant outbreaks in attempts to grow lobster in aquaculture facilities indicate that this virus is a very serious pathogen of Caribbean spiny lobster.

D.C. Behringer - UF

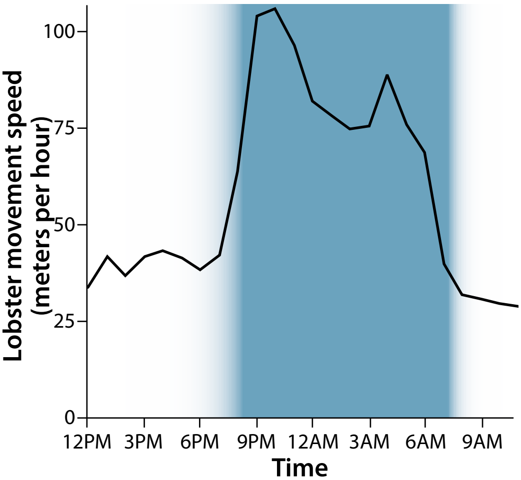
J. Sparado - UF

Species not infected after exposure to PaV1: Top: stone crab; Bottom: spider crab.

Adult Caribbean spiny lobsters are highly mobile

Rodney D. Bertelsen

A typical lobster travels more than a 0.8 kilometer (0.5 mile) per day. Some lobsters, however, are more sedentary, rarely moving more than a few hundred yards from their den. Lobsters move at speeds up to 0.53 km (0.33 mi) per hour. Most lobster movement occurs at night. During the day, lobsters stay inside rocky crevices to avoid daytime predators, such as triggerfish and sharks. Lobsters are generally creatures of habit. Tagging studies have shown that they often visit the same foraging ground at the same time several nights in a row. More often than not, they return to their same den area before dawn.



Lobsters feed and move predominantly at night. Most lobster movement occurs from 8 PM – 8 AM.

Queuing behavior

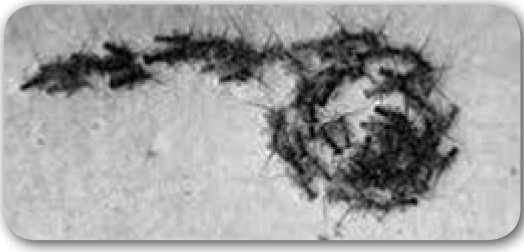
Sometimes lobsters move in lines containing less than 10 to more than 100 lobsters. These lines, called queues, provide an energy saving means to travel, as the lead lobster (which changes periodically) breaks the water resistance much like cyclists do during long bicycle races. Triggers of queuing behavior are not known for certain, and there may be several. However, hurricanes, tropical storms, cold late fall storms, decreasing water temperatures, turbid shallow waters, and generally less favorable conditions may cause lobsters living in shallow waters to travel several miles in queues to deeper water. In the absence of shelter, queuing lobsters may also engage in group defense and form an outward-facing rosette in an effort to ward off predators.

Lobster navigation

Spiny lobsters use the magnetic field of the Earth to find their way. This skill is called "true navigation" because lobsters can determine their actual position, not just a magnetic orientation to the north. Some birds, sea turtles, and a salamander also have this ability. Caribbean spiny lobsters are the first invertebrate found to demonstrate true navigation.

Reproductive movement

Another migration is made by adult female lobsters in the Florida Keys. During the spring and summer spawning season, adult females living in the relatively shallow Hawk Channel patch reefs, outlier reefs, and the fringing reef undergo a spawning migration to deeper waters to the fore reef to release eggs. The journey from patch reefs is roughly 3.2 km (2 mi) each way and each leg of the journey typically requires two nights of walking to complete. After releasing the eggs, females typically stay in deeper water for several days before returning to their resident reefs.



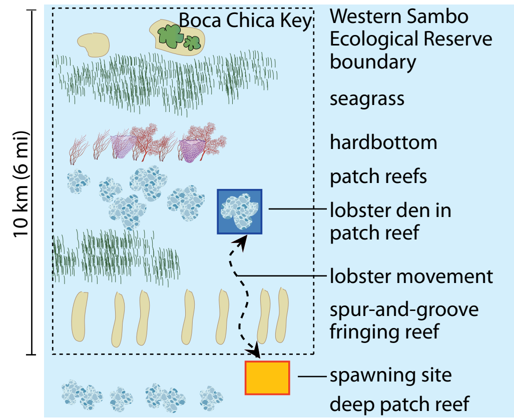
W.F. Herrnkind - FSU

Queuing lobsters forming a defense rosette.

Spiny lobster movements are tracked with acoustic technology

Rodney D. Bertelsen

The use of acoustic tags and receivers has revolutionized animal tracking in the ocean. Tracking studies conducted on land can use radio transmitters, but radio waves are absorbed by saltwater, so sound waves must be used instead. Small acoustic tags send out unique pulses of sound that are picked up by receivers strategically placed on the ocean floor. When data are downloaded, scientists can create a map that positions tagged lobsters in time and space. Acoustic receivers can listen for tags constantly and can hear the tags through the most turbid of waters. Acoustic technology reduces, but does not eliminate, the need for direct observations.

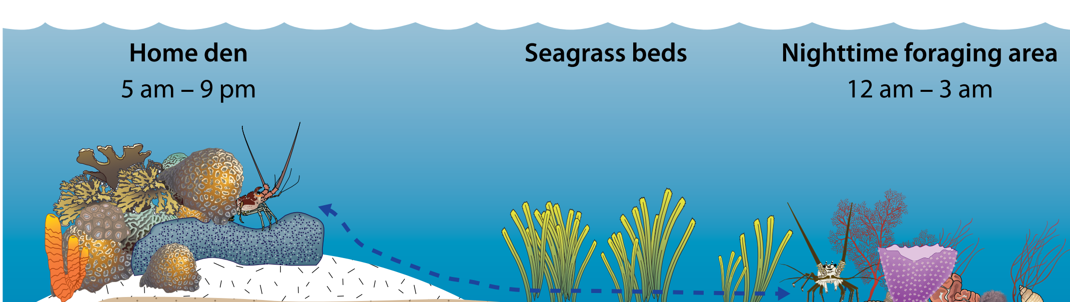


Spawning migration of a female lobster tagged on patch reef. This bird's eye view diagram shows that she traveled to the fore reef and returned to her den 4 days later. Scale is approximate.

L. Benvenuti
R.D. Bertelsen - FWC

Left: Lobsters can be tracked using miniature acoustic tags that ping their location to acoustic receivers. Right: Scientists deploy an acoustic receiver to track spiny lobster movement.

Lobsters are most active at night and do not give up their secrets easily. Acoustic tags are attached to the outside of the lobster carapace with epoxy. This process does not harm lobsters or affect their behavior. The lifetime of tags is up to 2 years, but the tags are lost when the lobster sheds its shell during molting. Because adult lobsters molt once or twice a year, studying long-term movements of lobsters is difficult. Acoustic tags can be detected up to 0.8 kilometer (0.5 mile) from receivers, but in areas with a lot of boat traffic, detection limits may be reduced by more than half. Thus, many closely spaced receivers are required to record movement over long distances.



Lobsters are most active at night, leaving their den to look for food.

Several techniques are used to harvest spiny lobsters

Kerry E. Maxwell

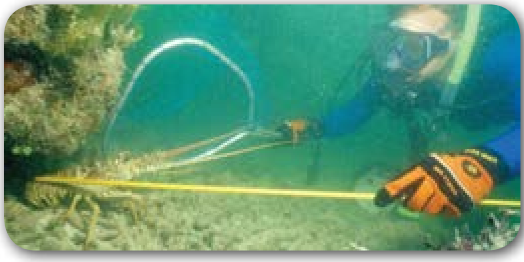
Spiny lobsters are harvested commercially using traps, bully nets, and by diving. Recreational fishers may not use traps; they collect lobsters primarily by hand with snorkel or SCUBA gear. To regulate harvest of lobsters, there is a minimum harvestable size, limits on the number of lobsters divers can collect, and limits on the number of traps a fisherman can deploy. There is also a closed season during the early summer months when lobsters are breeding (http://myfwc.com/rulesandregs/Saltwater_Regulations_lobster.htm).

Harvest method	Average landings (1998-2008)	
	Kilograms (kg)	Pounds (lbs)
Commercial trap	2,118,000	4,669,000
Commercial dive	191,000	422,000
Commercial bully net	9,000	19,000
Commercial other	13,000	28,000
Recreational fishers	647,000	1,427,000
Total	2,978,000	6,565,000

Average fishing season landings (pounds) in Florida by harvest method.

Trapping

Commercial trappers harvest the bulk of the lobsters landed in Florida. They fish predominantly with wooden traps distributed in waters surrounding southeast Florida. Traps are generally baited with fish heads, cow hide, or pig feet, as well as several sublegal-sized lobsters to attract legal-sized lobsters.



L. Benvenuti

Diver using a tickle stick and net to catch a lobster.

FWC

Bully nets are used to collect lobsters at night.

Sublegal lobsters used as bait are kept in live wells until they are needed. Commercial fishers use uniquely painted buoys to identify their traps that are pulled out of the water and onto the vessel using a winch.

Diving

Commercial and recreational divers typically use the same methods to catch lobsters. Divers "tickle" the lobsters out of their dens using tickle sticks and guide them into nets.

Bully netting

The least common method to catch lobsters is bully netting. Bully netters fish in shallow waters at night when lobsters are foraging or migrating away from their dens. Netters shine a light on the exposed lobsters and use a maneuverable net attached to a long pole to capture them.

By the numbers

- Average annual recreational lobster fishing licenses issued: 135,000.
- About 43,000 people participate in the 2-day special sport season.
- Commercial landings in Florida account for about 6% of the total commercial Caribbean landings.

Animal Diversity

No-take zones are safe havens for Caribbean spiny lobsters

Carrollyn Cox

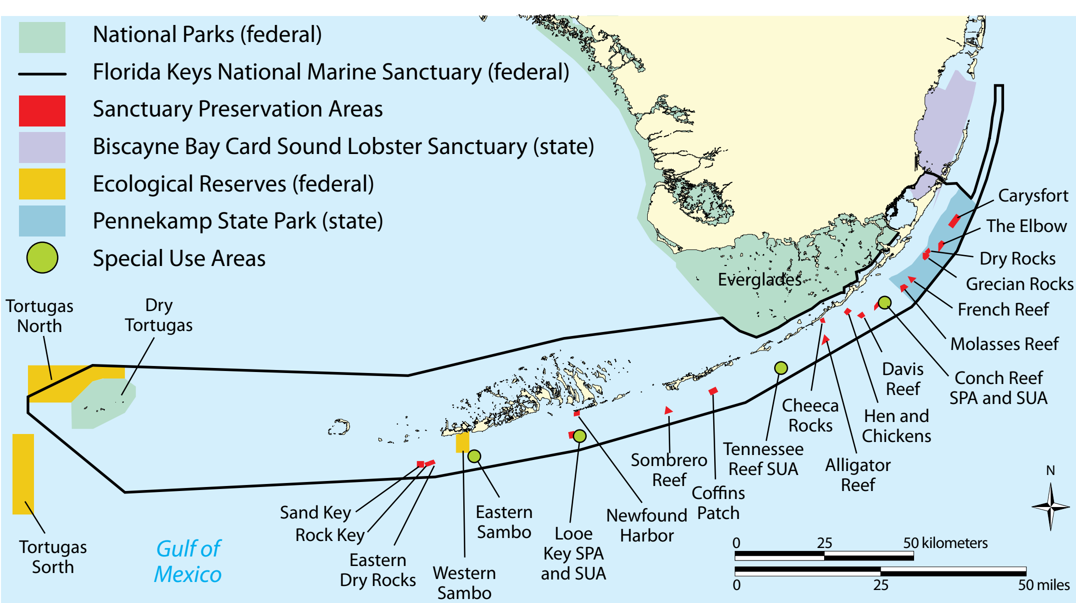
No-take zones are a form of a Marine Protected Area that has been temporarily or permanently closed to fishing and other extractive activities to protect fish stocks and natural habitats. No-take zones can enable a portion of the ecosystem to recover from the effects of fishing or other perturbations. One of the benefits of some no-take zones is that fishermen have reported larger catches close to the zone boundaries because of the "spillover" effect of species protected within the no-take zone. Most no-take zones in south Florida were created for purposes other than protecting lobsters. The Biscayne Bay-Card Sound Lobster Sanctuary, however, was designated "to be a nursery sanctuary for the purpose of protecting the spiny lobster" (Florida Administrative Code 68B-11.001).

In the early 1970s, very large female lobsters in Dry Tortugas National Park did not produce eggs because large males were nearly absent. All lobster fishing in the Park was banned in 1974. By 1997, very large female lobsters carried as many as 2 million eggs per brood as large males were no longer scarce. Lobsters in Western Sambo Ecological Reserve are now larger on average than lobsters outside the reserve. Research has revealed that there are also more legal-sized lobsters per unit area inside the reserve than outside.

South Florida no-take zones

Florida Keys National Marine Sanctuary protected zones (established 1997):

- 18 Sanctuary Preservation Areas;
- 4 Special Use Areas;
- 2 Ecological Reserves;
- Everglades National Park (closed to all lobster fishing since 1974);
- Biscayne Bay-Card Sound Lobster Sanctuary (established 1984);
- Dry Tortugas National Park (closed to all lobster fishing since 1974); and,
- John Pennekamp Coral Reef State Park Exclusion Zones (10 coral formation protection zones closed to all lobster fishing since 1995).



Caribbean spiny lobster no-take zones in south Florida.

You can help to protect Caribbean spiny lobsters

Dave Eaken

Spiny lobsters are heavily fished throughout their range, both by commercial and recreational fishers. In many regions of the Caribbean, they are nearly overfished. In Florida, recreational lobster fishing is very popular among divers and snorkelers of all ages and abilities. In a typical season, recreational lobster divers land about 22% of the total lobster catch statewide. The majority of those lobsters are caught in a flurry during the 2-day special sport season and the first few weeks of the regular season in early August. As the number of residents and visitors steadily increases each year in Florida, ethical and responsible fishing practices are more important than ever, particularly for lobsters and their habitat.

Ways to be a responsible lobster fisher

- Release all egg-bearing female lobsters unharmed.
- Handle undersized lobsters with care and release them unharmed.
- Only use allowable gear to collect lobsters.
- Place anchor in bare sand, not on coral or live bottom habitats.
- Follow the daily and season possession limits: myfwc.com/rulesandregs/Saltwater_Regulations_lobster.htm.

C. Cox - FWC

Recreational lobster fishing is a part of south Florida life.

Gentle handling of undersized lobsters incidentally caught is important to the health of the lobster and the overall "health" of the fishery. Lobsters are often damaged during capture. Sometimes an antenna is broken or one or more of their legs are pulled off. If the lobster is legal size, damage during capture is not that important. But, what if the lobster is not big enough to keep? Undersized lobsters released with injury use energy for repair instead of growth. An injured lobster is also more susceptible to predation and disease. If damaged too severely, the injured lobster will die.

C.F. Lewis - FWC

Lobster traps placed on top of coral can kill coral and diminish lobster habitat. Place traps in sandy areas.

Florida is home to other lobster species

Cynthia F. Lewis

Other spiny lobsters

Spiny lobsters, also known as langosta or rock lobsters, are a family (Palinuridae) of about 45 species worldwide and are found in almost all warm seas, including the Caribbean and the Mediterranean Sea. Other names for spiny lobsters are crayfish, sea crayfish, crawfish, and bugs. Spiny lobsters have long, thick, spiny antennae and lack claws. Other than the Caribbean spiny lobster (*Panulirus argus*), there are four other species in the family that occur in south Florida.

Spotted spiny or Spanish lobster
Panulirus guttatus

C.F. Lewis - FWC

- Spotted, ornately colored
- Live entirely on shallow reefs
- Do not usually den together

Red-banded or Long-handed lobster
Justitia longimanus

M.A. Moe Jr. - MML

- Found in deeper waters 46 – 91 meters (150 – 300 feet) off coral reef slopes
- Total body length is 15 cm (6 in)
- Only males have the large claw-like front legs

Green or Smooth-tail spiny lobster
Panulirus laevicauda

T. Matthews - FWC

- Line of small spots along edge of tail, upper surface of the tail not spotted
- Commercially important in Brazil

Copper furry or Caribbean furry lobster
Palinurellus gundlachi

FWC

- Hides among rocks and coral
- Body covered with short hairs
- Maximum total length is 15 centimeters (6 inches)

Slipper lobsters

Slipper lobsters are also known as shovel-nosed or bulldozer lobsters (Family Scyllaridae). The 70 species found worldwide occur in shallow waters to depths of 610 m (2000 ft). Their tails are edible. They are clawless and recognized by their broad, flat antennae plates which project forward on their head. The three species described below are found in south Florida, usually clinging to surfaces under rocky ledges. Like spiny lobsters, they are typically most active at night.

Spanish lobster
Scyllarides aequinoctialis

T. Ziegler - NPS

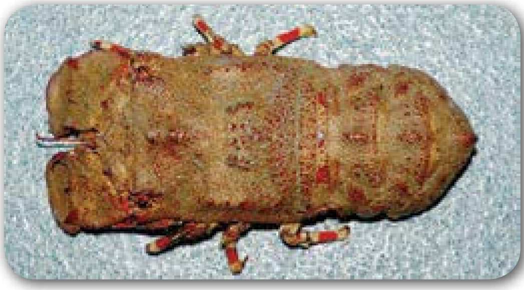
- Maximum total body length is over 30 cm (12 in)
- Slow moving
- Body color is a mix of purple, reddish-brown, or orangish-brown
- Yellow legs with tiny brown spots

Brown or Sculptured mitten lobster
Parribacus antarcticus

C.F. Lewis - FWC

- Brownish-purple coloring
- Usually less than 20 cm (8 in) long

Ridged slipper lobster
Scyllarides nodifer



Wikimedia

- Conspicuously red-banded legs
- Can reach 36 cm (14 in) in length
- Digs through the sand, feeding on small crustaceans and marine worms

Not found in Florida waters

NOAA

Clawed Lobsters (Family Homaridae), such as the familiar American or Maine lobster, are not closely related to Caribbean spiny or slipper lobsters, and are not found in Florida waters.

Animal Diversity

Introduction citations

1. Wikipedia. Biodiversity. Available from: http://en.wikipedia.org/wiki/Biodiversity (Updated 23 Feb 2011; cited 23 Feb 2011). *Etymology and definition of "biodiversity."*
2. Ruban N. 2010. Biodiversity. Scienceray, 11 June 2010. Available from: http://scienceray.com/earth-sciences/paleontology/biodiversity/ (Cited 23 Feb 2011). *Biodiversity is the variation of life forms within a given ecosystem, or on the entire Earth. Biodiversity is often used as a measure of the health of biological systems.*
3. Ehrlich PR, Ehrlich AH. 1981. Extinction: The Causes and Consequences of the Disappearance of Species. New York, New York: Random House Inc. 305 p. *Why biodiversity is important and why species go extinct.*
4. Wilson EO. 1988. Biodiversity. Washington, DC: National Academy Press. 521 p. A collection of papers contributed to the National Forum on Biodiversity. *Topics covered include the importance and challenges in maintaining biodiversity and principal issues in conservation biology and resource management.*
5. Florida Museum of Natural History. Estuarine and Marine Waters. Available from: http://www.flmnh.ufl.edu/fish/southflorida/everglades/estuarine/estuarine.html (Cited 23 Feb 2011). *Estuarine and marine waters of south Florida harbor over 500 species of fish.*
6. The Center for International Environmental Law. What is Biodiversity and Why is it Important? Available from: http://www.ciel.org/Biodiversity/WhatIsBiodiversity.html (Cited 23 Feb 2011). *Human activities have raised the rate of extinction to 1,000 times its usual rate. An estimated two of every three bird species are in decline worldwide, one in every eight plant species is endangered or threatened, and one-quarter of mammals, one-quarter of amphibians and one-fifth of reptiles are endangered or vulnerable.*
7. Wikipedia. Ecological extinction. Available from: http://en.wikipedia.org/wiki/Ecological_extinction (Updated 15 Mar 2010; cited 23 Feb 2011). *Examples of population declines (ecological extinction) of keystone species that result in changes to community structure.*
8. Lessios HA. 1988. Mass mortality of *Diadema antillarum* in the Caribbean: What have we learned? Annu Rev Ecol Syst. 19:371-393. *Loss of grazing by sea urchins resulted in increased algal growth on reefs. The Caribbean-wide loss provides an opportunity to study an ecological "catastrophe" that is between short-term, localized perturbations studied by ecologists and long-term, spatially widespread, usually irreversible events studied by paleontologists.*
9. Tuxill J, Bright C. 1999. Sharing the planet: Can humans and nature co-exist? Effects of urban growth. U.S.A. Today, Society for the Advancement of Education, Jan. 1999. BNET CBS Interactive Business Network. Available from: http://findarticles.com/p/articles/mi_m1272/is_2644_127/ai_53630956/pg_2/?tag=content;col1 (Cited 23 Feb 2011). *Discussion of reasons so many animals are in peril. For example, many mammals are relegated to precarious existences because their habitats are fragmented, remnant patches that are mere ecological shadows of their former selves.*
10. United Nations Environment Programme. About International Year of Biodiversity. Available from: http://www.unep.org/iyb/about_iyb.asp (Cited 23 Feb 2011). *Species are becoming extinct at the fastest rate known in geological history, and most of these extinctions are tied to human activity. Public knowledge and involvement is required to correct this problem.*
11. University of California. 2007. Historical overkill of marine megafauna has triggered the current ocean crises. Available from: http://www.universityofcalifornia.edu/news/article/3452 (Cited 23 Feb 2011). *Vast populations of whales, manatees, dugongs, monk seals, sea turtles, swordfish, sharks, giant codfish, and rays have been removed from the sea and changed the character of marine ecosystems.*
12. Jackson JBC, Kirby MX, Gerger WH, Bjondal KA, Botsford LW, Bouarque BJ, Bradbury RH, Cooke R, Erlandson J, Estes JA, Hughes TP, et al. 2001. Historical overfishing and the recent collapse of coastal ecosystems. Science 293: 29-637. *Ecological extinction caused by overfishing precedes all other pervasive human disturbance to coastal ecosystems, including pollution, degradation of water quality, and anthropogenic climate change. Historical abundances of large consumer species were fantastically large compared to current populations.*
13. Semmens BX, Buhle ER, Salomon AK, Pattengill-Semmens CV. 2004. A hotspot of non-native marine fishes: evidence for the aquarium trade as an invasion pathway. Mar Ecol Prog Ser. 266:239-244. *Since 1999, 16 non-native marine fish species from 32 locales in the western Atlantic have been observed by the REEF Fish Survey Project.*
14. Li HW (ed.). Non-native Species. National Biological Service, Oregon Cooperative Fishery Unit, Oregon State University. Available from: http://biology.usgs.gov/status_trends/static_content/documents/olrdocs/Nonative.pdf (Cited 24 Feb 2011). *A compendium of scientific papers on non-native species in the United States. The economic cost incurred because of non-native species in the United States reaches billions of dollars. Non-native species damage agricultural crops and rangelands, contribute to the decline of commercially important fishes, spread diseases that affect domestic animals and humans, and disrupt vital ecosystem functions.*
15. Whitfield PE, Gardner T, Vives SP, Gilligan MR, Courtenay Jr WR, Ray GC, Hare JA. 2002. Biological invasions of the Indo-Pacific lionfish (*Pterois volitans*) along the Atlantic coast North America. Mar Ecol Prog Ser. 235:289–297. *Although two species of lionfish are present, the red lionfish,* Pterois volitans *and the black lionfish,* Pterois miles. P. volitans *comprises the vast majority of the invasive population. The lionfish exhibit the typical characteristics of invasive species: they grow quickly, reproduce frequently, have no functional predators, and are extremely effective predators.*
16. Albins MA, Hixon MA. 2008. Invasive Indo-Pacific lionfish, *Pterois volitans*, reduce recruitment of Atlantic coral-reef fishes. Mar Ecol Prog Ser. 367:233-238. *Lionfish caused significant reductions in the recruitment of native fishes by an average of 79% over the 5 week duration of the experiment. This strong effect on a key life stage of coral-reef fishes suggests that invasive lionfish are already having substantial negative impacts on Atlantic coral reefs.*
17. Lapointe BE, Barile PJ, Littler MM, Littler DS, Bedford BJ, Gasque C. 2005. Macroalgal blooms on southeast Florida coral reefs: I. Nutrient stoichiometry of the invasive green alga *Codium isthmocladum* in the wider Caribbean indicates nutrient enrichment. Harmful Algae 4:1092-1105. *Beginning in the summer of 1990, spectacular blooms of unattached* Codium isthmocladum *developed on deep coral reef habitats in southern Palm Beach County and northern Broward County.*
18. Lapointe BE. 1997. Nutrient thresholds for bottom-up control of macroalgal blooms on coral reefs in Jamaica and southeast Florida. Limnol Oceanogr. 42:1119-1131. *A bloom of* Codium isthmocladum *in southeast Florida was triggered by dissolved inorganic nitrogen from wastewater.*
19. Thayer GW, Powell AB, Hoss DE. 1999. composition of larval, juvenile, and small adult fishes relative to changes in environmental conditions in Florida Bay. Estuaries 22:518-533. *There was an apparent shift*

toward a planktonic-feeding fish community following seagrass die-off and ensuing phytoplankton blooms.

20. Butler IV MJ, Hunt JH, Herrnkind WF, Childress M, Bertelsen R, Sharp W, Matthers T, Field JM, Marshall HG. 1995. Cascading disturbances in Florida Bay, Florida (U.S.A.): cyanobacterial blooms, sponge mortality, and their impact on juvenile spiny lobsters (*Panulirus argus*). Mar Ecol Prog Ser. 129:119-125. *Small bloom cells clog feeding passages of sponges and result in their death. Juvenile lobster habitat is destroyed.*
21. National Aeronautics and Space Administration, Goddard Space Flight Center. 2003. Blackwater turns the tide on Florida coral. Available from: http://www.nasa.gov/centers/goddard/news/topstory/2003/0423blackwater.html (Updated 23 Feb 2008; cited 24 Feb 2011). *In early 2002, a patch of "black water" spanning over 60 miles in diameter formed off southwestern Florida and contributed to severe coral reef stress and death in the Florida Keys.*
22. Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute. Red Tide Current Status Statewide Information. Available from: http://research.myfwc.com/features/view_article.asp?id=9670 (Cited 24 Feb 2011). *Current status of red tide events in Florida.*
23. Florida Fish and Wildlife Conservation Commission. 2011. Commercial Fisheries Landings in Florida. Available from: http://www.myfwc.com/research/saltwater/fishstats/commercial-fisheries/landings-in-Florida/ (Updated 03 May 2011; cited 01 Aug 2011). *Summary of commercial fisheries landings in Florida from 1986 to 2010.*
24. Miller CL, Ohs CL, Creswell RL. 2007. Candidate Species for Florida Aquaculture: Caribbean Spiny Lobster, *Panularis argus*. University of Florida, IFAS Extension, FA147. Available from: http://aquanic.org/species/shrimp/documents/spinylobster.pdf http://aquanic.org/species/shrimp/documents/spinylobster.pdf (Cited 24 Feb 2011). *Natural history, culture, market, and diseases of the Caribbean spiny lobster.*
25. Yeung C, Lee TN. 2002. Larval transport and retention of the spiny lobster, *Panulirus argus*, in the coastal zone of the Florida Keys, USA. Fish Oceanogr. 11:286-309. *The association of older larvae with the Florida Current front supports the hypothesis that spiny lobster larval recruits come from upstream sources in the Caribbean.*
26. National Oceanic and Atmospheric Administration, National Marine Fisheries Service. Fish Watch. Caribbean Spiny Lobster (*Panularis argus*). Available from: http://www.nmfs.noaa.gov/fishwatch/species/car_spiny_lobster.htm (Updated 11 Aug 2009; cited 24 Feb 2011). *Life history and habitat requirements of the Caribbean spiny lobster.*
27. Cox C, Hunt JH. 2005. Change in size and abundance of Caribbean spiny lobsters *Panulirus argus* in a marine reserve in the Florida Keys National Marine Sanctuary, USA. Mar Ecol Prog Ser. 294:227-239. *Most lobsters harvested are just over the legal limit of 76.2 mm (3 in) carapace length.*
28. Butler MJ, Behringer DC, Shields JD. 2008. Transmission of *Panulirus argus* virus 1 (PaV1) and its effect on the survival of juvenile Caribbean spiny lobster. Diseases of Aquatic Organisms 79:173-182. *PaV1 is highly infectious and lethal to juvenile* P. argus*, particularly early benthic juveniles in the wild, and, hence, is a threat to mariculture.*
29. Island Press. 2007. Millennium Ecosystem Assessment. Toolkit for Understanding and Action. Washington, DC: Island Press. 23 p. Available from: http://islandpress.org/assets/library/27_matoolkit.pdf (Cited 24 Feb 2011). *Humankind is living beyond our means: some 60 percent of the ecosystem services examined, including fisheries and fresh water, are being degraded or used in ways that cannot be sustained. Protect the whole ecosystem, not just selected parts.*

Further reading

Adams AJ, Dahlgren CP, Kellison GT, Kendall MS, Layman CA, Ley JA, Nagelkerken I, Serafy JE. 2006. Nursery function of tropical back-reef systems. Mar Ecol Prog Ser. 318:287-301. *A review of nursery functions of back-reef habitats.*

Ault JS (ed.). 2008. Biology and Management of the World Tarpon and Bonefish Fisheries. Boca Raton, FL: CRC Press. 441 pp. *Chapters on the biology, life history, population dynamics, fisheries, and ecosystem-based management of tarpon and bonefish.*

Ault JS, Bohnsack JA, Smith SG, Luo J. 2005. Toward sustainable multispecies fisheries in the Florida U.S.A. coral reef ecosystem. Bull Mar Sci. 76:595-622. *The ecosystem goods and services provided by coral reefs are threatened by increased exploitation and environmental changes from a rapidly growing human population. An ecosystem-based perspective and a systems science analysis framework was adopted to assess and improve sustainable multispecies reef fisheries in the Florida Keys.*

Ault JS, Smith SG, Bohnsack JA, Luo J, Harper DE, McClellan DB. 2006. Building sustainable fisheries in Florida's coral reef ecosystem: positive signs in the Dry Tortugas. Bull Mar Sci. 78:633-654. *Results after 3 years of monitoring areas closed to fishing suggest that no-take marine reserves, in conjunction with traditional management, can help build sustainable fisheries while protecting the Florida Keys coral-reef ecosystem.*

Behringer DC, Butler IV MJ, Shields JD. 2006. Avoidance of disease by social lobsters. Nature 441:421. *Healthy lobsters avoid infected lobsters.*

Behringer DC, Butler IV MJ, Shields JD. 2008. Ecological and physiological effects of PaV1 infection on the Caribbean spiny lobster (*Panulirus argus* Latreille). J Exp Mar Biol Ecol. 359:26-33. *PaV1 infections are nearly always lethal, but prior to succumbing to the disease, infection may impact lobster movement, growth, and survival that effect the transmission of the virus.*

Bert TM, Harrison RG. 1988. Hybridization in western Atlantic stone crabs (genus *Menippe*): Evolutionary history and ecological context influence species interactions. Evolution 42(3):528-544. *Two distinct species of marine crabs (*Mennippe mercenaria *and* Mennippe adina*) interbreed in two distinct areas of the southeastern United States.*

Bohnsack JA, Ault JS. 1996. Management strategies to conserve marine biodiversity. Oceanography 9:73-82. *Marine biodiversity is threatened by habitat destruction, environmental changes, and over exploitation. Preventing reductions in biodiversity and promoting sustainable resource use requires new management strategies, more effective education, and strong research.*

Brusher JH, Schull J. 2009. Non-lethal age determination for juvenile goliath grouper *Epinephelus itajara* from southwest Florida. Endang Species Res. 7:205-212. *Dorsal spines are a reliable method for ageing goliath grouper between the ages of 0 and 6 yr.*

Carr A. 1967. So Excellent a Fishe: A natural history of sea turtles. Garden City, NY: Natural History Press. 248 p. *Classic work on sea turtles.*

Cox C, Hunt JH, Lyons WG, Davis GE. 1997. Nocturnal foraging of the Caribbean spiny lobster, *Panulirus argus*, at offshore reefs of Florida, USA. Mar Freshwater Res. 48:671-680. *Description of the diet of Caribbean spiny lobsters.*

Delgado GA, Glazer RA, Hawtof D, Aldana Aranda D, Rodríguez-Gil LA, de Jesús-Navarrete A. 2008. Do queen conch (*Strombus gigas*) larvae recruiting to the Florida Keys originate from upstream sources?

Evidence from plankton and drifter studies. In Grober-Dunsmore R, Keller BD (eds.). Caribbean connectivity: Implications for marine protected area management. Proceedings of a Special Symposium, 9-11 November 2006, 59th Annual Meeting of the Gulf and Caribbean Fisheries Institute, Belize City, Belize. Marine Sanctuaries Conservation Series ONMS-08-07. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 195 p. *A study with plankton trawls and drift vials to determine the origin of queen conch (*Strombus gigas*) larvae recruiting to the Florida Keys supports the fact that most of the larvae found in the Keys originated from the Keys and that the queen conchs found there are dependent on local recruitment. Therefore,restoration efforts should target local spawning populations.*

Faunce CH, Serafy JE. 2006. Mangroves as fish habitat: 50 years of field studies. Mar Ecol Prog Ser. 318:1-18. *Review of published studies on the utilization of mangroves by fishes.*

Frias-Torres S. 2006. Habitat use by juvenile goliath grouper, *Epinephelus itajara*, in the Florida Keys, USA. Endang Species Res. 2: 1-6. *The first underwater census and habitat preferences study on juvenile goliath grouper in the Florida Keys.*

Frias-Torres S, Barroso P, Eklund AM, Schull J, Serafy J. 2007. Activity patterns of juvenile goliath grouper, *Epinephelus itajara*, in a mangrove nursery. Bull Mar Sci. 80: 587-594. *Study on movement patterns of juvenile goliath grouper in mangroves.*

Hart KM. 2008. Tracking sea turtles in the Everglades. Endangered Species Bulletin: 33:26-29. *Relatively inaccessible headwater areas and shallow nearshore environments may provide previously unknown foraging areas for juvenile green sea turtles.*

Hartman DS. 1979. Ecology and behavior of the manatee (*Trichechus manatus*) in Florida. Amer Soc Mammal. Special Publ. 5, 153 p. *Detailed information on the biology and population dynamics of the manatee, including man-manatee interactions.*

Jackson JCB. 1997. Reefs since Columbus. Coral Reefs 16: S23-S32. *Caribbean coastal ecosystems were severely degraded long before ecologists began studying them.*

Knowlton N. 2001. Sea urchin recovery from mass mortality: New hope for Caribbean coral reefs? Proc Natl Acad Sci. 98:4822-4824. *Confirmation of the importance of herbivory for the maintenance of healthy coral reefs, and encouraging evidence that formerly abundant organisms can linger at extremely low densities for nearly two decades, and then rebound.*

Lavalli KL, Spanier E (eds.). 2007. The Biology and Fisheries of the Slipper Lobster. Boca Raton, FL: CRC Press, Crustacean Issues 17. 420 p. *A collection of scientific research papers on the biology, aquaculture and fisheries for slipper lobsters, including a section describing Florida's three slipper lobster species, their ecology, and the Florida Scyllarid fishery.*

Lavalli KL, Herrnkind WL. 2009. Collective defense by spiny lobster (*Panulirus argus*) against triggerfish (*Balistes capriscus*): effects of number of attackers and defenders. New Zeal J Mar Fresh Res. 43:15-28. *When threatened, lobsters assemble into outward facing, rosette-like groups, remain coherent in their spacing, and defend themselves by parrying with their spinous antennae.*

Lee TN, Williams E. 1999. Mean distribution and seasonal variability of coastal currents and temperature in the Florida Keys with implications for larval recruitment. Bull Mar Sci. 64:35-56. *Seasonal cycles of currents and winds favors enhanced larval recruitment in the fall season of persistent northeast winds that can cause a coastal countercurrent over the entire length of the Keys from Key Largo to the Dry Tortugas, combined with seasonal maximum onshore surface transports and minimum downstream flow in the Florida Current.*

Longley WH, Hildebrand SF. 1941. Systematic catalogue of the fishes of Tortugas, Florida with observations on color, habits, and local distribution. Pap Tortugas Lab Carnegie Inst. 34, 331 pp. *Comprehensive list of the fishes of the Tortugas with notes on their biology.*

Luo J, Serafy JE, Sponaugle S, Teare PB, Kieckbusch D. 2009. Movement of the gray snapper (*Lutjanus griseus*) among subtropical seagrass, mangrove, and coral reef habitats. Mar Ecol Prog Ser. 380:255-269. *Tagged and tracked fish confirm the use of mangrove, seagrass, and coral reef habitats by gray snapper. The study supports a strategy of conserving both inshore and offshore habitats to protect all stages in the life history of gray snappers.*

Lutz PL, Musick JA (eds.). 1996. The Biology of Sea Turtles, Vol. 1. Boca Raton, FL: CRC Press, Inc. 448 p. *Comprehensive reference on the biology and ecology of sea turtles.*

Lutz PL, Musick JA, Wyneken J (eds.). 2002. The Biology of Sea Turtles, Vol. 2. Boca Raton, FL: CRC Press, Inc. 772p. *Comprehensive reference on the biology and ecology of sea turtles. Includes information on social and economic aspects of sea turtle conservation.*

Mazzotti FJ, Best GR, Brandt LA, Cherkiss MS, Jeffery BM, Rice KG. 2009. Alligators and crocodiles as indicators for restoration of Everglades ecosystems. Ecol Indic 9(6):S137-S149. *Trends of crocodilian populations relative to hydrologic changes allow assessment of positive or negative trends in ecosystem restoration.*

Mazzotti FJ, Brandt LA. 1994. Ecology of the American alligator in a seasonally fluctuating environment. In: Davis SM, Ogden JC (eds.). Everglades: The Ecosystem and Its Restoration. Delray Beach, FL: St. Lucie Press. p. 485-506. *Historically, alligators were abundant in peripheral marshes of the Everglades, and now they are most abundant in central sloughs. Restoration should include hydrological management that restores alligator habitat in areas where they were formally abundant.*

Mazzotti FJ, Brandt LA, Moler P, Cherkiss MS. 2007. American crocodile (*Crocodylus acutus*) in Florida: recommendations for endangered species recovery and ecosystem restoration. J Herpetol. 41:121-131. *As crocodiles continue to increase in number and expand into new areas, interactions with humans will occur more frequently. The challenge of integrating a recovering population of the American crocodile with an ever-increasing use of coastal areas by humans will be the final challenge in successful recovery of this once critically endangered species.*

McMurray SE, Blum JE, Pawlik JR. 2008. Redwood of the reef: growth and age of the giant barrel sponge *Xestospongia muta* in the Florida Keys. Mar Biol. 155: 159-171. *Although age extrapolations for very large sponges are subject to error, the largest sponges on Caribbean reefs may be in excess of 2,300 years, placing the giant barrel sponge among the longest-lived animals on earth.*

Miller C, Kosmynin V. 2008. The effects of hurricane-deposited mud on coral communities in Florida. Proc Internat Coral Reef Symp. Session 18, 5 pp. *Multiple hurricanes during 2004 deposited widespread accumulations of mud on the Atlantic and Gulf coasts of Florida that resulted in lethal conditions for many filter-feeding species and reduced recruitment for most benthic species.*

Moe Jr. M.A. 1991. Lobsters: Florida, the Bahamas, and the Caribbean. Plantation, FL: Green Turtle Publications. 510 p. *Detailed description of the spiny lobster life history, description of Florida's lobsters, information about aquaculture and other lobster rearing practices, and an overview of the recreational and commercial lobster fisheries in Florida and throughout the Caribbean.*

NOVA. 1992. Private Lives of Dolphins. WGBH, Boston, MA.

DVD. *A documentary on observations of researchers on dolphins in their natural environments, including information on their brainpower, society, evolution, communication, mating, temperament, and politics.*

Phillips BF, Cobb JS (eds.). 1980. The Biology and Management of Lobsters. Vol 1. Physiology and Behavior. New York: Academic Press. 463 p. *Detailed review of biology, physiology, and behavior of lobsters.*

Phillips BF, Cobb JS (eds.) 1980. The Biology and Management of Lobsters. Vol 2. Ecology and Management. New York: Academic Press. 390 p. *Detailed review on the ecology and management of lobsters.*

Phillips BF, Kittaka J (eds.). 2000. Spiny Lobsters: Fisheries and Culture, 2nd Edition. Malden, MA: Fishing News Books, Blackwell Science Ltd. 704 p. *A comprehensive review of the biology, ecology, aquaculture, and management of spiny lobsters worldwide. Includes sections on the status of the Caribbean spiny lobster in Florida.*

Porter JW, Porter KG (eds.). 2001. The Everglades, Florida Bay, and Coral Reefs of the Florida Keys. Boca Raton, FL: CRC Press. 1000 p. *A compilation of scientific papers on various aspects of the south Florida ecosystem stressing that freshwater and marine ecosystems are linked by hydrology and require an ecosystem-scale approach for effective management.*

Rudloe J. 1979. Time of the Turtle. New York: Alfred A. Knopf. 273 p. *A blend of biology, personal anecdotes, and folklore about sea turtles.*

Sharp WC, Bertelsen RD, Leeworthy VR. 2005. Long term trends in the recreational lobster fishery of Florida, United States: landings effort, and implications for management. New Zeal J Mar Fresh Res. 39:733-747. *Description of the recreational fishery for spiny lobsters in Florida, fishing methods, and per person landings.*

Starck II WA. 1968. A list of fishes of Alligator Reef, Florida with comments on the nature of the Florida Reef Fish fauna. Undersea Biol. 1:5-40. *Classic work on fishes of Alligator reef.*

Van Meter VB. 1989. The Florida Manatee. Florida Power and Light, Miami, FL. 41 p. *Summary of biology and ecology of manatees in Florida.*

Van Meter VB. 1992. Florida's Sea Turtles. Florida Power and Light, Miami., FL. 46 p. *Summary of biology and ecology of Florida's sea turtles.*

Website references

Bester C. Gray Snapper. Florida Museum of Natural History. Available from: http://www.flmnh.ufl.edu/fish/gallery/descript/graysnapper/graysnapper.html (Accessed 25 Feb 2011). *Distribution, habitat, and biology of gray snapper.*

Chan Tak-Chuen T, Padovani Ferrera B. 2006. *Epinephelus itajara*. In: IUCN 2010. IUCN Red List of Threatened Species. Version 2010.4. Available from: http://www.iucnredlist.org/details/7857/0 (Accessed 25 Feb 2011). *The worldwide status of the goliath grouper is explained in the International Union for the Conservation of Nature (IUCN) Red List of Threatened Species.*

Clark C. 2010. Voracious lionfish wreaks havoc in Florida Keys. The Miami Herald. Available from Physorg.com at: http://www.physorg.com/news185130378.html (Accessed 25 Feb 2011). *Lionfish have steadily spread throughout the Florida Keys.*

Colugo11. 2006. The Life of a Sponge. Tree of Life. Available from: http://tolweb.org/treehouses/?treehouse_id=4291 (Accessed 25 Feb 2011). *General information about the life history of sponges.*

Culik B. 2010. Whales and Dolphins. World Wildlife Fund. Available from: http://www.cms.int/reports/small_cetaceans/index.htm (Accessed 25 Feb 2011). *Distribution, population, behavior, and threats to whales and dolphins. Distribution, population size, biology, and behavior of the Atlantic spotted dolphin-* Stenella frontalis.

Defenders of Wildlife. 2011. Sea Turtles: Kemp's Ridley. Available from: http://www.defenders.org/wildlife_and_habitat/wildlife/sea_turtles (Accessed 25 Feb 2011). *Information on life history of Kemps ridley sea turtle.*

Defenders of Wildlife. 2011. Florida Manatee- *Trichenchus manatus latirostrus*. Available from: http://www.defenders.org/wildlife_and_habitat/wildlife/manatee.php (Accessed 25 Feb 2011). *Facts about the Florida manatee.*

Endangered Species Research. 2009. Range-wide status and conservation of the Goliath grouper. Available from: http://www.int-res.com/abstracts/esr/v7/n3/ (Accessed 25 Feb 2011). *A theme issue of the journal Endangered Species Research including 12 open access papers.*

Florida Fish and Wildlife Conservation Commission. Spiny Lobster: *Panularis argus*. Available from: http://myfwc.com/rulesandregs/Saltwater_Regulations_lobster.htm (Accessed 25 Feb 2011). *Summary of lobster fishing regulations in Florida.*

Florida Fish and Wildlife Conservation Commission, Fish and Wildlife Research Institute. Lobster. Available from: http://research.myfwc.com/features/category_sub.asp?id=2326 (Accessed 25 Feb 2011). *Links to articles on the anatomy, ecology, and fishery of the Caribbean spiny lobster.*

Florida Fish and Wildlife Conservation Commission. Differences Between Crocodiles and Alligators. Available from: http://myfwc.com/wildlifehabitats/Crocodile_Differences.htm (Accessed 25 Feb 2011). *Description and pictures showing differences between crocodiles and alligators.*

Florida Fish and Wildlife Conservation Commission. 2006. Queen conch, Florida's Spectacular Sea Snail. Sea Stats, Fish and Wildlife Research Institute, St. Petersburg, FL. 4 p. Available from: http://research.myfwc.com/engine/download_redirection_process.asp?file=queenconch_4434.pdf&objid=-1595&dltype=product (Accessed 24 Feb 2011). *Biology and distribution of the queen conch.*

Florida Keys National Marine Sanctuary. Invasive Lionfish. Available from: http://floridakeys.noaa.gov/lionfish.html (Accessed 25 Feb 2011). *Information on where to report all sightings of lionfish.*

Goddard J. 2008. Lionfish devastate Florida's native shoals. The Sunday Times, October 20, 2008. Available from: http://www.timesonline.co.uk/tol/news/environment/article4974396.ece (Accessed 25 Feb 2011). *Lionfish invade Florida's waters.*

Hammond PS, Bearzi G, Bjørge A, Forney K, Karczmarski L, Kasuya T, Perrin WF, Scott MD, Wang JY, Wells RS, Wilson B. 2008. *Tursiops truncatus*. The IUCN Red List of Threatened Species- Bottlenose dolphin (Least Concern). Version 2010.4. Available from: http://www.iucnredlist.org/apps/redlist/details/22563/0 (Accessed 25 Feb 2011). *Range, population, ecology, and major threats to the bottlenose dolphin.*

Jacoby C, Walters L, Baker S, Blyler K. 2009. A Primer on Invasive Species in Coastal and Marine Waters. Florida Sea Grant College Program, SGEP 60, 2 pp. Available from: http://edis.ifas.ufl.edu/pdffiles/sg/sg07500.pdf (Accessed 25 Feb 2011). *Background information on invasive species and their management.*

Kennedy J. 2011. 7 Species of Sea Turtles. About.com. Available from: http://marinelife.about.com/od/vertebrates/tp/seaturtlespecies.htm (Accessed 25 Feb 2011). *Descriptions and food requirements of seven species of marine sea turtles.*

Long-spined sea urchin, *Diadema antillarum*. Available from: http://www.diadema.org/ (Accessed 25 Feb 2011). *Summary of the importance of the long-spined sea urchin to Caribbean coral reefs.*

Marx JM, Herrnkind WF. 1986. Species profiles: Life Histories and Environmental Requirements of Coastal Fishes and Invertebrates (South Florida): Spiny Lobster. U.S. Fish Wildl. Serv. Biol. Rep. 82(11.61). U.S. Army Corps of Engineers, TR EL-82-4. 21 p. Available from: http://www.nwrc.usgs.gov/wdb/pub/species_profiles/82_11-061.pdf (Accessed 24 Feb 2011). *Life history of the Caribbean spiny lobster.*

Mazotti FJ. 2009. American crocodiles (*Crocodylus acutus*) in Florida. University of Florida IFAS Pub. WEC 38, 4 pp. Available from: http://edis.ifas.ufl.edu/uw157 (Accessed 25 Feb 2011). *Life history and factors limiting population success of the American crocodile.*

McMurray S, Pawlik J. 2008-2009. Caribbean barrel sponges. Coral Science.org. Available from: http://www.coralscience.org/main/articles/climate-a-ecology-16/caribbean-sponges (Accessed 25 Feb 2011). *Biology and threats to sponges on coral reefs.*

Martin A. Moe, Jr. And then they were gone: The urchins and the reef. Available from: http://www.blackbeard-cruises.com/diadema-sea-urchin-research-trips.htm (Accessed 25 Feb 2011). *Summary of the loss and potential restoration of long-spined sea urchins onto coral reefs.*

Moller MP, Cherkiss MS, Mazotti FJ. The American crocodile: A story of recovery. University of Florida, 5 p. Available from: http://crocdoc.ifas.ufl.edu/posters/croc_p1.htm (Accessed 25 Feb 2011). *Human population growth and development in south Florida is diminishing the restricted distribution of the American crocodile at the northernmost limit of its range.*

National Oceanic and Atmospheric Administration, National Marine Fisheries Service. Fish Watch. Queen conch (Strombus gigas). Available from: http://www.nmfs.noaa.gov/fishwatch/species/queen_conch.htm (Updated 14 May 2009; accessed 25 Feb 2011). *Life history, habitat, and management of the queen conch in Florida.*

Robins RH. Biological Profiles: Goliath grouper. Available from: http://www.flmnh.ufl.edu/fish/gallery/descript/goliathgrouper/goliathgrouper.html (Accessed 25 Feb 2011). *Summary of distribution, life history and conservation of goliath grouper.*

Sadovy Y, Eklund AM. 1999. Synopsis of biological data on the Nassau grouper, Epinephelus striatus (Bloch 1792) and the jewfish *E. itajara* (Lichtenstein 1822). NOAA Technical Report NMFS 146. 65 pp. Available from: http://aquacomm.fcla.edu/2523/1/tr146.pdf (Accessed 25 Feb 2011). *A summary of the biology and life history of the goliath grouper (jewfish) and Nassau grouper.*

Sea Turtle Conservancy. 1996-2010. Information about Sea Turtles. Their Habitat and Threats to Their Survival. Available from: http://www.cccturtle.org/seaturtleinformation.php (Accessed 25 Feb 2011). *Information on the life histories and habitats of all sea turtles found in south Florida.*

See Florida Online. Florida Sea Turtle Information. Available from: http://www.seefloridaonline.com/turtles/ (Accessed 25 Feb 2011). *Life history, conservation, and turtle trivia of sea turtles found in Florida.*

Shubow D. 1969. Sponge fishing on Florida's east coast. Tequesta 29: 3-16. Available from: http://digitalcollections.fiu.edu/tequesta/files/1969/69_1_01.pdf (Accessed 25 Feb 2011). *Historical account of late 19th and 20th century sponge industry in the Biscayne Bay, the Florida Keys, Key West and Tarpon Springs.*

Stevely J, Sweat D. 2009. Florida's Marine Sponges: Exploring the Potential and Protecting the Resource. Florida Sea Grant College Program, SGEF-169, 5 p. Available from: http://edis.ifas.ufl.edu/sg095 (Accessed 25 Feb 2011). *A fact sheet on sponge biology and the sponge fishery.*

The Patek Lab, University of Massachusetts. 2009. Sound in the Sea: Spiny Lobsters. Available from: http://www.bio.umass.edu/biology/pateklab/sound-sea-spiny-lobsters (Accessed 25 Feb 2011). *How spiny lobsters make the rasping sound.*

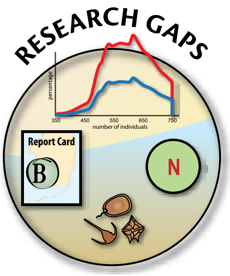
United States Fish and Wildlife Service, North Florida Ecological Services Office. Loggerhead Sea Turtle (*Caretta caretta*). Available from: http://www.fws.gov/northflorida/SeaTurtles/Turtle%20Factsheets/loggerhead-sea-turtle.htm (Updated 19 Jan 2011; accessed 25 Feb 2011). *Detailed information on range, population level and habitat of the loggerhead sea turtle.*

Zea S, Henkel TP, Pawlik JR. 2009. The Sponge Guide: a picture guide to Caribbean sponges. Available from: http;//www.spongeguide.org (Accessed 25 Feb 2011). *A picture guide to identification of Caribbean sponges.*

8. HUMAN CONNECTIONS

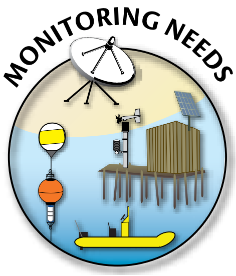
Human Connections
Chapter Recommendations

- Include input from **user groups** in management plans to maximize completeness and acceptance.
- Develop management plans to take into account the **connectivity of different habitats** so that plans are "ecosystem plans" and not confined to conservation of individual habitats.
- Coordinate among federal, state, and local management agencies to **reduce conflicts and confusion** over laws and regulations.
- Continually assess and revise the effectiveness of management plans as needed. **Adaptive management** is learning by doing.
- Include a **"no net loss" provision** in local management plans and develop guidelines for effective mitigation of unavoidable and illegal impacts to natural resources.
- Include provisions in restoration programs to **restore historically damaged communities** to improve ecosystem functions, because in some circumstances, maintaining the status quo of resources through a "no net loss" program may not be enough.



- Investigate effects of **mosquito control practices** on nontarget organisms.
- Assess and compare **fish stocks** managed by traditional management methods with those within Marine Protected Areas to provide important information for the development of future management strategies.
- Determine the effectiveness of Marine Protected Areas on replenishing "downstream" habitats by using innovative tagging experiments and/or use of **genetic markers** to quantify the source of recruiting organisms.
- Include other components of the ecosystem, in addition to fish stocks, in research and monitoring programs to assess the **effectiveness of Marine Protected Areas**.
- Develop criteria based on existing Marine Protected Area data to justify maintaining or altering their location, size, or shape.
- Analyze current speed and direction, as well as other physical or chemical oceanographic variables, as a prerequisite to consideration of **Marine Protected Area placement**.
- Research cost-effective **mitigation and restoration procedures** and the means to evaluate success.

Chapter title page: Loggerhead Key Lighthouse, Dry Tortugas. NPS.



- Evaluate **human uses** of resources systematically and periodically to ensure that adequate protections are in place.
- Monitor **compliance** with existing plans can help direct enforcement actions.
- Educate resource users to ensure acceptance and compliance with management plans. Surveys designed to assess knowledge of existing laws and regulations can reveal areas where additional **public outreach** is required.
- Monitor the **success of environmental restoration** to ensure that conditions are met and the restoration is successful.

NPS

Sooty terns at Dry Tortugas National Park.

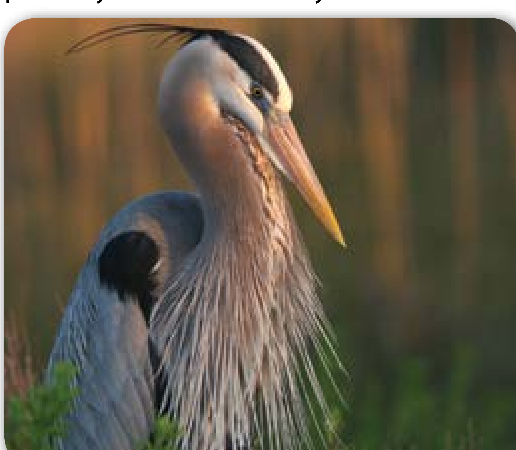
Human Connections

Introduction

Humankind relies on a healthy marine ecosystem for food, jobs, recreation, relaxation, transportation, security, and scientific study.[1] The south Florida marine ecosystem consists of many connected habitats: sandy beaches, bays and estuaries, tidal creeks, mangrove forests, seagrass meadows, hardbottom areas, patch reefs, soft bottom areas, bank reefs, and oceanic waters. The functioning of the whole ecosystem is dependent upon efficient functioning of its many physical, chemical, and biological components. For example, thriving populations of reef fishes depend upon healthy adjacent seagrass and mangrove habitats.

Humans have dramatically altered the entire south Florida ecosystem, and it currently shows signs of the consequences of overdevelopment, overexploitation, and overuse by burgeoning residential and visitor populations.[2] Development activities on upland areas can impact coastal waters by altering natural drainage characteristics and discharging pollutants that can alter nearshore salinity and water quality.

There are two main pathways to effect improvements to natural resources: preservation and management. These pathways are not mutually exclusive.


C. Anderson - USFWS

A great blue heron in Everglades National Park. Reaction to the egregious harvesting of wading birds for their feathers in the early 19th century led to birth of the conservation movement in the United States.

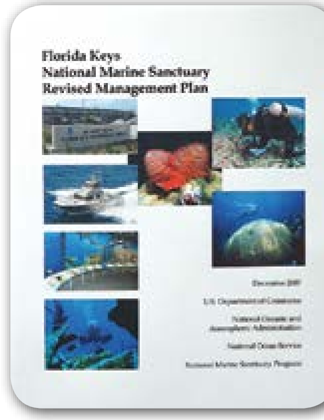
The recognition of the uniqueness and fragility of much of the wildlife and locales in south Florida has resulted in widespread support for efforts to protect wildlife and natural areas by placing especially important habitats into public ownership (i.e., preservation), thus removing them from potential loss to development. For example, the wasteful harvesting of wading birds in south Florida for the plume feather trade industry led President Theodore Roosevelt to begin the legacy of setting aside lands and waters dedicated to conserving wildlife.[3,4] The protection of millions of acres of public lands is a testament to the foresight of the responsible federal, state, and local agencies that recognized the need for effective ecosystem preservation and management of wilderness areas.

Not all natural areas can be preserved, but all can be effectively managed. The goal of environmental management is to ensure that the condition of natural resources is maintained or improved for the enjoyment of the current generation and generations to come. To be effective and defensible, management options should be based on sound scientific underpinnings. Because environmental resources may be used by many in different ways, managing for the good of the whole many times may conflict with uses of the resource by individual user groups. If management is to be effective and efficient, all user groups should contribute to the management planning process and become educated on the long-term goals and objectives of the management plan.[5] For instance, closing an area to fishing to protect the breeding stock of a fish species may be to the immediate detriment of commercial and recreational fishermen. However, if done correctly, closing an area to fishing may actually provide long-term benefits to fishing and be supported by fishermen.

The establishment of the Florida Keys National Marine Sanctuary (FKNMS) is a good example of the development of a management plan based upon existing scientific knowledge, and designed for multiple uses. The Florida Keys National Marine Sanctuary Act (1990) directed the National Oceanic and Atmospheric Administration to consider and promote "multiple uses" that are compatible with the primary purpose of resource protection. The Act also required that marine zoning be considered in the management plan and that an advisory council comprised of representatives from the various user groups be established. The goal of the advisory council is to make recommendations on management actions that are consistent with conservation, while minimizing conflicts and impacts. While not without controversy, for the first time on a large scale in the United States, the concept of marine zoning was applied to provide "something for everyone".[6] The zoning strategies included in the FKNMS Management Plan fostered acceptance and support by various user groups.[7]

Congress also recognized the importance of water quality in maintaining Sanctuary resources and directed the United States Environmental Protection Agency and the State of Florida to develop a Water Quality Protection Program for the FKNMS. This was the first such program ever developed for a marine sanctuary. Its purpose is to recommend corrective actions that address pollution sources and includes a long-term monitoring program to assess status and trends of water quality, seagrasses, and coral reefs. The Water Quality Protection Program action plan was based on a review of existing science. The plan was finalized in 1996 and included in the FKNMS Management Plan that was implemented in 1997.[8]

In 2003, the United States Coral Reef Task Force recommended the development of a similar management plan to address curtailment of water pollution on reefs located outside the boundaries of the FKNMS. The Southeast Florida Coral Reef Initiative, a Local Action Strategy, was developed to address coral reef conservation and management in southeast Florida north of the Florida Keys. The goals of the Southeast Florida Coral Reef Initiative are to characterize the existing condition of coral reefs, quantify the sources of pollution, and reduce land-based sources of pollution to coral resources in Miami-Dade, Broward, Palm Beach, and Martin Counties.[9] The Florida Area Coastal Environment Program is a research and monitoring effort designed to assess impacts of land-based sources of pollution on the Southeast Florida Reef System to assist in the development of science-based management.[10]



The Florida Keys National Marine Sanctuary Management Plan was implemented in 1997 and the Revised Management Plan was implemented in 2007.

One of the accomplishments of the management and planning efforts to date in the Florida Keys is documentation of the need to improve wastewater and stormwater treatment and disposal. Historically, many communities throughout south Florida were built with poorly functioning on-site wastewater disposal systems and the canals adjacent to those communities were found to have high nutrient concentrations and elevated concentrations of fecal coliform bacteria.[11] There is still scientific debate on how far from shore the detrimental impacts of the pollutants reach.

Findings and rulings concerning the development of the Monroe County Comprehensive Plan (1991 – 1995) led to the development of a work program and a schedule for corrective actions that culminated in the Monroe County Sanitary Wastewater Master Plan and the Monroe County Stormwater Master Plan. Completion of those management plans garnered wide acceptance that wastewater and stormwater pollutants rapidly enter nearshore waters and recommended site-specific corrective actions. Recognition of the fact that nearshore waters in the Florida Keys are nutrient enriched from land-based sources of pollution led to the passage of binding treatment and disposal requirements for all wastewater management facilities in Monroe County, including sewage treatment plants and on-site sewage treatment and disposal systems (OSTDS). Chapter 99-395, Laws of Florida, requires that all new sewage facilities, including OSTDS, permitted after June 18, 1999, comply with stringent effluent standards by July 1, 2010.[12] Passage of Chapter 99-395 forced local governments to initiate planning efforts to effect required changes to wastewater and stormwater treatment that are currently being enacted. Recently, the Florida Legislature extended the deadline for compliance of Chapter 95-395 to December 31, 2015.[13]

An important management strategy in areas where biological resources have declined is the establishment of preserved areas called Marine Protected Areas (MPAs), which are refuges where ocean life can recover and thrive. Unlike traditional management tools, such as fisheries regulations, MPAs focus on protecting the entire ecosystem within their borders. It is thought that protecting the areas within MPAs can contribute to a healthier and more resilient marine ecosystem that can better withstand a wide range of impacts, such as pollution and climate change.[14] Presidential Executive Order 13158 (2000) defines an MPA as "any area in the marine environment that has been reserved by federal, state, territorial, tribal, or local laws or regulations to provide lasting protection for part or all of the natural and cultural resources located within its boundaries." The Order calls for more effective and collaborative uses of MPAs as an ecosystem management tool.[15]


Wikimedia
No-take marine reserves provide protection for recreationally and commercially important species, such as the black grouper.

There are several different kinds of MPAs in place in south Florida. The FKNMS has designated Sanctuary Preservation Areas, Wildlife Management Areas, Ecological Reserves, Special Use Areas, and Existing Management Areas. MPAs can also be created to protect cultural resources (e.g., a ship wreck) for future generations. The greatest benefit to the ecosystem comes from the establishment of no-take marine reserves (NTMRs), in which all fishing, mineral extraction, and other habitat-altering activities are prohibited. It has been shown that in NTMRs worldwide, fish are larger, more abundant, and more diverse in comparison with areas open to fishing. Thus, establishment of NTMRs in areas with declining ecosystem health can help locally restore ecosystem functions and species abundance and diversity. It is thought that spillover from NTMRs will benefit surrounding areas.[16] Spillover includes fish or other organisms swimming across the NTMR boundary or increased spawning output from fish within NTMRs. Data from the Florida Keys show that this is the case for lobster,[17] black grouper, and snappers.[18]

An important lesson in effective management was learned during the establishment of the Tortugas Ecological Reserve (2002). The boundaries originally proposed for the Reserve were altered after commercial fishermen pointed out that implementation would close important commercial fishing grounds and not serve the intended purpose of the Reserve. After a series of meetings with user groups, the boundaries were modified to protect important breeding stocks that could help replenish the downstream reef tract. The new boundaries of the Reserve have been embraced by managers and commercial fishermen as a "win-win" situation, an important goal for any effective resource management strategies.[19,20]

The goal of all environmental management should be to leave the planet at least as good as our generation found it, and hopefully a little better, for the enjoyment of future generations. The development of an effective restoration program is an important tool in a viable environmental management program to meet that goal. Restoration is the process by which a damaged resource is renewed biologically, structurally, and functionally.

Damage to a biological community may occur by natural or human-induced activities. Natural damage may occur as a result of waves and storm surge, lightning strikes, droughts, fires, floods, and diseases. Human-induced damage may result from dredge and fill, poor land uses, boat groundings, propeller scars, resource destruction (e.g., overturning corals), pollution (e.g., sediment, nutrient, toxic), and overharvest.


NPS

Boca Chita lighthouse at Biscayne National Park. National Parks are managed for multiple uses.

Replacing natural resources lost through permitted activities is called "compensatory mitigation" and should be included as a condition of issued permits by regulatory agencies to achieve "no net loss" of resource functions and values. Enforcement actions taken against perpetrators of illegal activities, including boat groundings, dredging or filling, and discharging of pollutants must include development and implementation of an approved restoration plan to restore damaged resources, along with any civil or criminal penalties. Development and implementation of restoration plans is best accomplished by qualified individuals with experience in restoring the damaged community type. It should be recognized that restorations can be expensive, involving site preparation, planting or colonizing with native organisms, and monitoring success. Development of success criteria is a critical component of an acceptable restoration plan. Contingency plans must be considered if restoration criteria are not met.

Many habitats have been historically degraded and management plans should focus on their restoration. For example, approximately 50% of the original mangrove communities in the Florida Keys has been lost to development, and that loss has undoubtedly altered the structure and function of the coastal marine ecosystem. Some may view the existing condition as "natural," but that assumption is an example of a shifting baseline supposition. In such cases, a broad, active restoration program that is not solely associated with current permitting and enforcement activities is needed to improve existing conditions with a goal of restoring the biological community to historical baselines.

Marine ecosystems should be managed for multiple uses

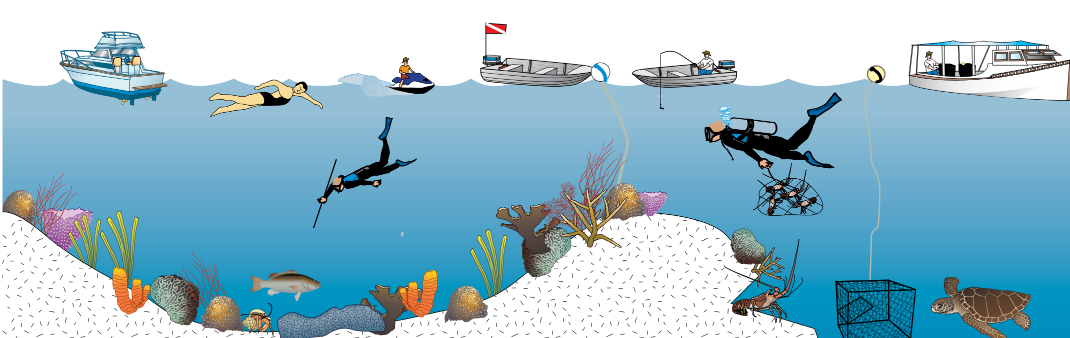
David A. Score

The mild, subtropical climate of south Florida and the coral reef ecosystem attract millions of tourists each year, and today, tourism comprises at least one third of the local economy. A full range of recreational opportunities offers something for everyone, including boating, swimming, sport fishing, diving, spear fishing, snorkeling, treasure hunting, bird watching, and relaxing. Clearly, management strategies to protect and sustain natural resources must consider these multiple, and potentially conflicting, uses and interests.

The south Florida marine ecosystem shows signs of the consequences of overdevelopment, overexploitation, and overuse. Humans have dramatically altered the system and now play a major role in the current and future makeup of the ecosystem. It is no longer "human versus nature" in south Florida, but rather "human in nature" or "human and nature." Marine resource managers must recognize this fact and develop strategies that consider and account for both environmental and socioeconomic sustainability. Incumbent with that responsibility is the need to recognize that we are ultimately managing people, as much as, if not more than, nature.

The continually growing population and increasing tourism set the stage for user conflicts and degradation of sensitive habitats and water quality of south Florida. The increased popularity of SCUBA diving sets up conflicts with recreational and commercial fishing. As sport fishing grew, conflicts developed with commercial fishing interests. Recreational boating has become more accessible and affordable; as a result, the number of boating accidents and physical destruction to coral and seagrass has increased exponentially. The advent of personal watercraft created concerns over noise, safety, and conflict with residents and flats fisherman. Thus, there was a compelling need in the Florida Keys to develop a comprehensive set of regulations and an acceptable suite of activities to provide for sustainable use, while protecting ecosystem structure and functions.

Regardless of the motivation, be it resource protection, safety, or quality of life, interests converged around effectively managing the uses of the marine environment. This recognition was particularly important and timely in the Florida Keys. The diminishing ecological health of the natural resources, the threat of oil drilling, and impacts of vessel groundings resulted in the establishment of the Florida Keys National Marine Sanctuary, a model of management for multiple uses in the marine environment.



Effective management can reduce user conflicts in marine environments.

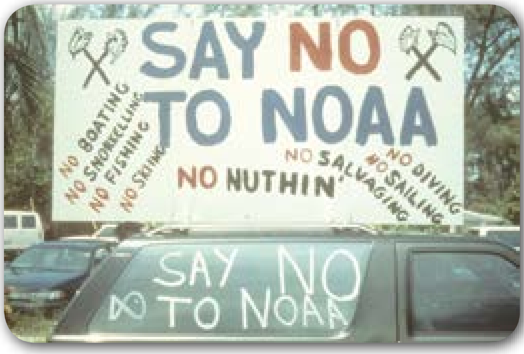
The Florida Keys National Marine Sanctuary is a model of managing for multiple uses

David A. Score

The Florida Keys National Marine Sanctuary Act was passed by Congress in 1990 in recognition of the national and international importance of the entirety of the Florida Keys ecosystem and the need to conserve the services and opportunities it provides for future generations. While several discrete conservation areas and parks had been established in south Florida and the Keys (e.g., National Park Service Organic Act 1916, National Wildlife Refuge System Act 1966, John Pennekamp Coral Reef State Park 1963), a unified approach to ecosystem management was lacking. While very specific in directing conservation and preservation, the Act directed the National Oceanic and Atmospheric Administration (NOAA) to consider and promote "multiple uses" of the Sanctuary that are compatible with the primary purposes of resource protection. It also "grandfathered" or exempted several existing activities, including traditional fishing practices.

Two other very powerful provisions were included in the Act that now serve as the basis for the National Marine Sanctuary approach to managing for multiple uses. These are the requirement to consider the use of marine zoning as part of a comprehensive management plan for the area and the establishment of an advisory council comprised of representatives from the various user groups to make recommendations on how to effectively manage the area, consistent with conservation, while minimizing conflicts and impacts. The Act also requires the management of the Sanctuary to be a joint effort between the State of Florida and NOAA.

The concept of comprehensive management through a joint trustee agreement between the state and federal government was not unanimously embraced. Part of the culture and allure of the Florida Keys is its independence at the "end of the road" and a sense of rugged individualism without extreme government intervention. The development and ultimate adoption of the final marine zoning scheme and regulations required a 7-year public dialogue and debate that was waged through public meetings and vetted through the newly formed Sanctuary Advisory Council.



NOAA

Keys residents expressed their concerns with the proposed Florida Keys National Marine Sanctuary (ca. 1995) before they understood how it would be managed.

While not without controversy, for the first time on a large scale in the United States, the concept of marine zoning was applied in a holistic way to provide "something for everyone" with a foundation in resource and habitat protection. Although not perfect, the marine zoning strategies have demonstrated success and, perhaps more importantly, developed acceptance and support with diverse user groups. Ultimately, compliance with the intent of the zones will dictate long-term success or failure. Education and enforcement efforts are required that entail continual investment, vigilance, and adaptive management. As new information becomes available on the status of and threats to the ecosystem (e.g., climate change, emerging uses), managers and stakeholders will need to periodically review and modify the current zoning strategy, building on the established fundamental process that went into the original designation.

The FKNMS Comprehensive Marine Zoning Strategy includes five categories of marine zones. Not all zones are nonconsumptive or exclusionary. To the contrary, many are designed to allow specific activities determined to be compatible, while minimizing or avoiding conflicts with other uses. The misconception of that fact is at the heart of the controversy over marine zoning. Taking time to become educated and understand the background, purpose, and objectives of this management tool can lead to greater support and acceptance. Less than 9% of the 10,000 km² (3900 mi²) Sanctuary is off limits to consumptive uses, such as fishing. Yet the strategic location of that 9% can yield maximum conservation benefits. Research and monitoring efforts on the response of key species after 15 years of protection have documented the benefits of the zoning plan to Sanctuary resources.

FKNMS

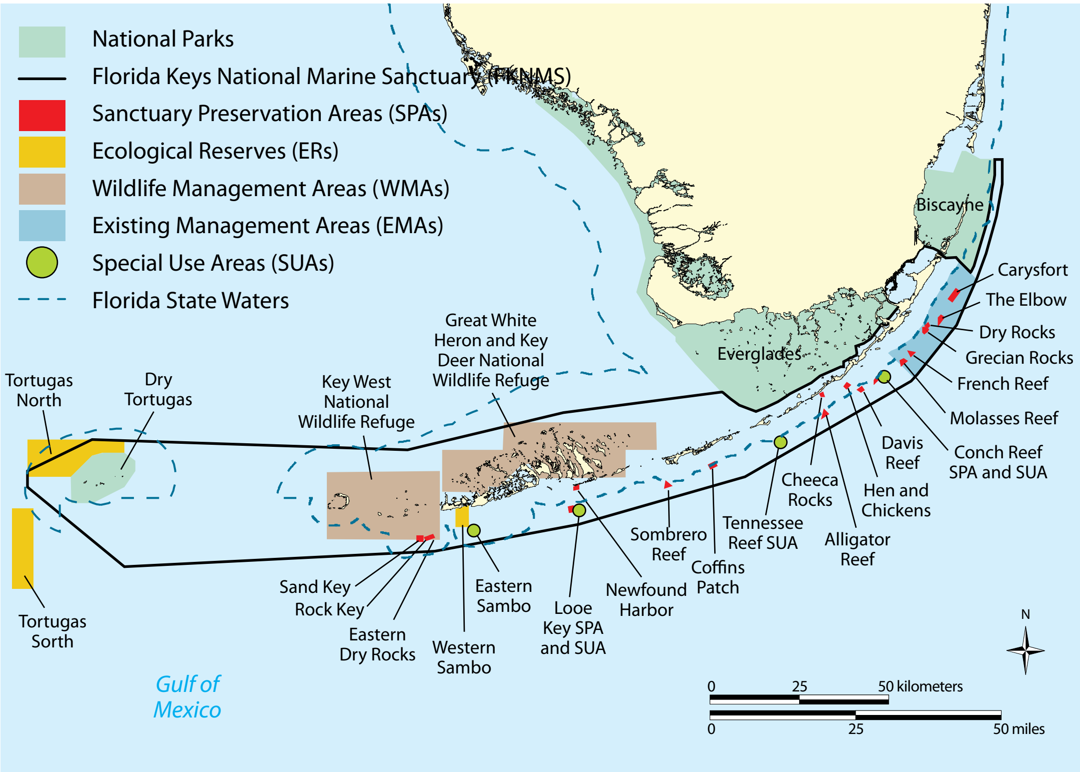
In 1999, Keys fisherman and other stakeholders participated in discussions to determine the boundaries for the proposed Tortugas Ecological Reserve.

W.L. Kruczynski - EPA

The Florida Keys Eco-Discovery Center in Key West opened in 2007 and provides educational opportunities through interactive exhibits that highlight the importance of sharing the rich natural habitats of the Florida Keys.

There are five management zone types in the Florida Keys National Marine Sanctuary

David A. Score



Map showing the boundary of the Florida Keys National Marine Sanctuary (FKNMS) and location of special management zones.

Sanctuary Preservation Areas

Purpose: to protect shallow, heavily used reef areas where conflicts occur among user groups and where concentrated visitor activity leads to habitat or resource degradation. There are 18 Sanctuary Preservation Areas totaling 22 km^2 (8.5 mi^2), or 0.2% of the Sanctuary. Taking of any marine organisms and anchoring are generally prohibited. Mooring buoys are available to facilitate compatible uses.

Did you know?

Research and monitoring shows that Sanctuary Preservation Areas have greater numbers and sizes of fish than many surrounding areas.

Ecological Reserves

Purpose: to protect biodiversity by setting aside areas with minimal human disturbance, allowing areas to return to a natural state and thereby preserving the diverse range of resources and habitats throughout the Sanctuary. The reserves encompass large, contiguous, diverse habitats to protect and enhance natural spawning, nursery, and residence areas for the replenishment and genetic protection of fish and other marine life. There are two Ecological Reserves: Western Sambo and Tortugas, totaling 550 km^2 (210 mi^2) or 5.5% of the Sanctuary. All consumptive activities are prohibited and nonconsumptive activities are limited to those compatible with resource protection.

Did you know?

The Tortugas South Ecological Reserve protects spawning aggregations of black grouper and mutton snapper, and grouper have increased their numbers and size in the Ecological Reserve since establishment in 2001.

Wildlife Management Areas

Purpose: to minimize disturbance to sensitive or endangered wildlife and their habitats by managing the mode and/or timing of access while preserving public access to the greatest extent practicable. These areas typically include bird nesting, resting, and feeding areas; turtle nesting beaches; and other sensitive habitats. There are 27 Wildlife Management Areas in the Sanctuary; 22 of them are co-managed with the United States Fish and Wildlife Service. Access restrictions may include no-access buffers, no-motor zones, no-wake zones, and closed zones and may apply to time periods or areas.

Did you know?

Wildlife Management Areas include some of the best catch and release fishing areas in the world for bonefish, tarpon, and permit.

Existing Management Areas

Purpose: to support the specific role and function of management areas that were established prior to and complement the 1997 Florida Keys National Marine Sanctuary Management Plan. Existing Management Areas are managed in partnership with the Sanctuary and provide added protection of certain habitats and species. The Sanctuary regulations supplement the existing authorities to augment comprehensive protection. There are 21 Existing Management Areas in the Sanctuary that include State Parks, National Wildlife Refuges, and pre-existing National Marine Sanctuaries. Fifteen are administered by the Florida Department of Environmental Protection, four by the United States Fish and Wildlife Service, and two by the National Oceanic and Atmospheric Administration.

Did you know?

The Key Largo National Marine Sanctuary was the second National Marine Sanctuary ever designated and protects the federal waters of what used to be Pennekamp State Park until 1974.

Special Use Areas

Purpose: to designate discrete areas for research, education, or other special purposes that may include facilitating recovery or restoration of injured or degraded resources, facilitating access to or use of Sanctuary resources, and preventing user conflicts. Research-only areas also provide control areas to evaluate effects of activities in similar habitats. There are four permanent Special Use Areas that are designated for research only: Conch Reef, Tennessee Reef, Looe Key Patch Reef, and Eastern Sambo. Other Special Use Areas may be established on a case-by-case basis and are a valuable tool for adaptive management.

Did you know?

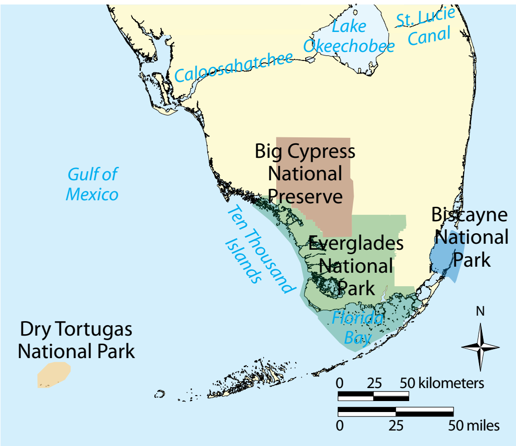
The Conch Reef research-only Special Use Area encompasses the *Aquarius* Undersea Laboratory that has served as an underwater research laboratory since 1993.

The National Park Service provides protection of marine and upland environments in south Florida

Larry Perez and Alice Clarke

The Greater Everglades Ecosystem is an expansive 47,000 km^2 (18,000 mi^2) region, extending from the Kissimmee River north of Orlando to the southernmost Florida Keys. Owing largely to its geography, this vast watershed embraces a richly diverse amalgam of tropical and subtropical life between the forested uplands of central Florida to the submerged coral reefs of the Dry Tortugas. As testament to its distinctive qualities, four National Park Service units have been designated amidst the south Florida landscape. Collectively, Everglades, Biscayne, and Dry Tortugas National Parks and the Big Cypress National Preserve protect nearly 1 million hectares (2.5 million acres) of land and sea. These areas not only showcase a matchless ecosystem teeming with natural splendors, but also preserve forever a collection of resources that chronicle the history of human existence in south Florida. Not surprisingly, many of the values that proved important in times past remain critical to both current and future populations.

Each of the south Florida national park areas is managed in accordance with applicable legislation and policy. The Organic Act of 1916 created the National Park Service and charged the agency with an enduring mission: to conserve the natural, cultural, and historical objects present in the lands it oversees, while providing for their enjoyment in such a manner as "will leave them unimpaired for the enjoyment of future generations." In addition to this broad, sweeping mandate, the enabling legislation for each unit clearly identifies the purpose for which each was established and prescribes the manner in which each shall be administered. Ambiguities in these formal laws are clarified in the National Park Service Management Policies, which provide guidance on a host of issues including park planning,



Location of four National Park Service units in south Florida.

visitor use, natural and cultural resource management, commercial services, and facilities.

Few areas in the United States can boast four major units of the National Park Service within a half day of travel by automobile. South Florida national park areas coexist in delicate balance with the growing cities that flourish outside their borders. For more than a century, the needs of residents and industry have dictated the manner in which the south Florida landscape has been altered, often to the detriment of natural systems. Largely under the auspices of the Comprehensive Everglades Restoration Plan, federal and state resource managers are now reevaluating how to better manage what natural resources remain in south Florida. Facing the uncertainties of climate change, restoration of ecosystem health is a necessary precursor to saving the parks in the future. South Florida national park units will most certainly face escalating pressures and impacts, and can expect continued struggles in fulfilling their mandate of preservation of resources for the enjoyment of future generations.

Everglades National Park includes terrestrial, freshwater, and marine habitats

Larry Perez and Alice Clarke

Size: 6000 km² (2300 mi²)
Dedicated: 1947

Pursuant to the legislation that first authorized Everglades National Park (48 Stat. 816), lands acquired for its creation:

"…shall be permanently reserved as a wilderness, and no development of the project or plan for the entertainment of visitors shall be undertaken which will interfere with the preservation of the unique flora and fauna and the essential primitive natural conditions now prevailing in this area."

President Truman's dedication of Everglades National Park in 1947 set a precedent in the conservation efforts of our nation. Unlike the national parks that came before it, Everglades earned federal protection not for its geology or scenic vistas, but rather for the unique assemblage of life that thrives upon the landscape. Today, the Park continues to serve principally as a vast biological reserve, where present-day visitors can marvel at the unparalleled natural heritage found in south Florida.

Everglades National Park preserves the largest, contiguous remnant of the historical watershed that author and activist Marjory Stoneman Douglas dubbed the "River of Grass." Nearly 89% of the Park has been set aside as the Marjory Stoneman Douglas Wilderness, the largest such Congressionally designated area east of the Rocky Mountains. This designation protects a portion of the only subtropical ecosystem in the continental United States, the largest stand of sawgrass prairie in North America, and the largest protected mangrove ecosystem in the Northern Hemisphere.

NPS

Wildlife abounds in Everglades National Park. More than 320 species of birds have been observed within the Park, including many wading birds, such as the great egret.

NPS

The River of Grass is vegetated predominantly by sawgrass that filters water as it moves south toward Florida Bay.

The Park boasts a richly diverse collection of temperate and tropical life that thrives amidst warm temperatures and seasonal fluxes of flood and drought. Flat elevations, frequent fires, occasional frosts, and powerful tropical storms worked in concert over millennia to forge a mosaic of habitats important for the survival of life in the area. In addition to the dazzling seasonal displays of wildlife for which the Everglades has become synonymous, the Park provides sanctuary and habitat for a variety of rarely encountered threatened and endangered species. Often, the same resources that serve to sustain this wildlife also nurture the human community that concurrently depends upon the climate, water, and associated ecosystem services provided by the Everglades.

Seasonal pulses of freshwater from the north are important for recharging aquifers that serve as an important source of clean drinking water for neighboring urban communities. These flows are equally vital in preserving the integrity and function of nationally important estuaries downstream. The mangrove forests and the open waters of Florida Bay comprise roughly two thirds the area of Everglades National Park. These shallows provide sanctuary to a wide array of marine species that are of great ecological, commercial, and recreational value along the south Florida coast.

Although Everglades National Park commands attention for the aggregations of wildlife that inhabit its seemingly endless expanse of land and sea, it also relays subtle reminders of human struggle in south Florida. The Park preserves lands that served as the ancestral homes of several Native American cultures, many of which are known only from the remnants they have left behind. The Park is of cultural importance to both the Miccosukee Tribe of Indians of Florida and the Seminole Tribe of Florida, and continues to sustain resources of importance to them. The Park also protects a wealth of historical and cultural resources that serve to chronicle the arrival, settlement, and survival of divergent cultures in south Florida.

For its many values, Everglades National Park has received international recognition via three intergovernmental treaties. The Park has simultaneously been designated a United Nations World Heritage Site, a Man and the Biosphere Reserve, and a Wetland of International Importance. Yet despite such recognition, securing the long-term health of the Park remains a difficult task. Unlike the remote national parks of the American West, Everglades is immediately bordered by an ever-burgeoning south Florida community. As population pressures increase, it is likely that balancing the resource needs of growing urban areas against those of the remnant ecosystem will remain an ongoing challenge.

More information about Everglades National Park can be found at "nps.gov/ever".


NPS

The diversity of habitat types in Everglades National Park includes tree islands in the "sea" of sawgrass. Tree islands are considered key indicators of the health of the Everglades ecosystem because of their sensitivity to both flood and drought conditions. Tree islands also act as a sink for nutrients in the ecosystem and may play an important role in regulating nutrient dynamics.

Dry Tortugas National Park has major cultural and natural resources

Larry Perez and Alice Clarke

Size: 259 km² (100 mi²)
Dedicated: 1935

Fort Jefferson National Monument was established by Presidential Proclamation in 1935, and authorized as Dry Tortugas National Park by Congress in 1992. The enabling legislation (P. L. 102-525) is specific to the management purposes of the Park:

"…to preserve and protect for the education, inspiration, and enjoyment of present and future generations nationally significant natural, historic, scenic, marine, and scientific values in South Florida…"

Thanks to its unique position along a major migratory route, the Park provides a haven for a myriad of wildlife. During the spring and summer months, the seven islands of the Tortugas host active nesting colonies of several coastal birds, including sooty terns, masked boobies, brown noddy terns, and magnificent frigate birds. For some species, the islands of the Dry Tortugas represent the only known nesting colony in the continental United States. Bush Key is closed during spring and summer months to protect nests, and Hospital and Long Keys are closed all year.

Due largely to their relatively remote location, the marine habitats of the Dry Tortugas are often considered the most pristine of the Florida Keys Reef Tract. Seagrass, corals, and hardbottom communities host a bevy of ocean life, including sea turtles, lobster, mollusks, and more than 450 species of fish. The action of ocean currents helps disperse juveniles of numerous commercially and recreationally important species northeastward along the full stretch of the Florida Keys. To preserve the function and integrity of the ecosystem, roughly 46% of the Park has been set aside as a Research Natural Area (RNA), a designation that permits nonconsumptive use while allowing self-renewal of Park resources.

W.L. Kruczynski - EPA

One of the largest 19th century coastal fortifications in the United States, the massive brick structure of Fort Jefferson on Garden Key bears silent witness to the myriad ways these islands were used for generations. Spanish explorers, pirates, privateers, soldiers, scientists, and park rangers have all sought refuge here.

Las Tortugas

Ponce de León discovered these islands in 1513 and named them "Las Tortugas," meaning "the turtles" in Spanish, because of the abundance of sea turtles that were captured to provision his ships with fresh meat. But there was no fresh water—the Tortugas were dry.

Establishment of the RNA begins a new chapter in nearly 200 years of scientific study in the Dry Tortugas. Early surveys by John James Audubon and Louis Agassiz would eventually lead to the establishment of the Tortugas Laboratory by the Carnegie Institution of Washington in 1904 on Loggerhead Key, the first tropical marine laboratory of its kind. Complementing the adjacent Tortugas Ecological Reserve of the Florida Keys National Marine Sanctuary, the RNA provides the National Park Service and its partner organizations an unprecedented opportunity to continue scientific research on a variety of fish species in an area relatively free from direct human pressures and impacts.

More information about Dry Tortugas can be found at "nps.gov/drto".

Biscayne National Park faces a unique suite of management challenges

Larry Perez and Alice Clarke

Dedicated: 1968

Biscayne National Monument was established by Congress (P. L. 90-606) in 1968 and subsequent acts added additional area and reclassified the unit as a national park. The primary purpose of the Park is to:

"… preserve and protect for the education, inspiration, recreation, and enjoyment of present and future generations a rare combination of terrestrial, marine, and amphibious life in a tropical setting of great natural beauty…"

Centuries before the creation of Biscayne National Park, the area served as the stage for native cultures, international explorers, pirates, soldiers, smugglers, wreckers, and entrepreneurs. Unlike most national parks, Biscayne is primarily an underwater preserve. Although the Park boasts a nearly unbroken stretch of mangrove shoreline and several offshore islands, these comprise only a small fraction of the total area in the unit.

Due to its location between tropical and temperate regions, the diversity of life present in Biscayne rivals that of most national parks in the United States. The mangrove coast and offshore keys help frame the waters of Biscayne Bay, which are a major fish nursery ground that supports both recreational and commercial pursuits. Historically, freshwater flows from the west helped temper salt concentrations, providing a salinity gradient capable of hosting a wide spectrum of coastal life. Seagrasses blanket much of the Bay bottom, providing important habitat for countless species of mollusks, sponges, crustaceans, and fish.

To the east, in the waters just seaward of the chain of offshore keys, lie the northernmost reaches of the third largest barrier coral reef tract in the world. Teeming with an abundance of life, these reefs are among the most biologically and genetically rich ecosystems on the planet.

NPS

Biscayne National Park protects four primary ecosystems: the mangrove forest along the mainland shoreline, the shallow southern portion of Biscayne Bay, the northernmost Florida Keys, and a portion of the third largest barrier coral reef in the world.

The Park faces a unique suite of management challenges. Since the turn of the 20th century, agriculture, urbanization, and tourism caused dramatic changes to the natural ecosystems of the Park. Unbridled growth in Miami-Dade County, where development has already engulfed northern Biscayne Bay, continues to result in changes to the natural physical structure, ocean circulation, depth and topography, and water quality patterns within the Park.

Escalations in both population and water-based recreation will likely continue to present management challenges in the future, including propeller scars, coral damage, and water pollution. Loss of seasonal freshwater flows from the west have altered hydrologic patterns in the Bay, but coupled with anticipated effects from sea-level rise, these realities could have even greater negative impacts on the long-term health of many Park resources.

More information about Biscayne National Park can be found at "nps.gov/bisc".

Human Connections

Big Cypress National Preserve is one of the most pristine watersheds in the Everglades

Larry Perez and Alice Clarke

Size: 2950 km^2 (1140 mi^2)
Dedicated: 1974

Big Cypress National Preserve was established by Congress (P.L. 93-440) in 1974. The primary purpose of the preserve, the first of its kind in the system, was:

"…to assure the preservation, conservation, and protection of the natural, scenic, hydrologic, floral and faunal, and recreational values of the Big Cypress Watershed in the State of Florida and to provide for the enhancement and public enjoyment thereof."

The Big Cypress Swamp of southwest Florida is a distinct region within the Greater Everglades Ecosystem. The majority of Big Cypress Swamp is currently protected via a patchwork of federal, state, and private conservation areas, the largest of which is the Big Cypress National Preserve. Within its borders are an assortment of plant and animal communities that rival the diversity of adjacent Everglades National Park. Dependent upon these communities is a collection of imperiled species, including the largest remnant population of the endangered Florida panther (*Puma concolor*).

NPS

The Florida panther is an endangered species that persists in limited numbers in the wilds of south Florida. Although recent conservation efforts provide new hope for the species, continued habitat loss threatens full recovery.

Although it once boasted trees of immense girth, the Big Cypress Swamp is named for its spatial extent. The variety of habitats present is largely the result of an interplay between water and rock. Fed by seasonal rains formed over the Everglades, geologic variation in the area substrate provides a range of conditions from xeric (dry) uplands to perennially flooded wetlands.

The Big Cypress National Preserve represents one of the most pristine watersheds in the Greater Everglades Ecosystem. Historically, surface flows from the basin nourished nearby areas, including both Shark River Slough and the Ten Thousand Islands, and helped ensure the productivity of downstream freshwater and estuarine systems. However, canals and levees just outside the perimeter of the preserve now divert downstream flows and several major roadways bisect the preserve and act as impediments to flow. Coupled with rising sea level, the disruption of freshwater flows from the Preserve may herald changes in downstream vegetative communities. It is hoped that the successful completion of several projects related to the Comprehensive Everglades Restoration Plan will result in greater ecological connectivity to areas in and around the preserve.

Recreational uses compatible with safeguarding the natural and ecological integrity of the area can be permitted in national preserves. Thus, unlike most areas afforded protection as national parks, Big Cypress National Preserve is managed to accommodate a suite of historical uses, including hunting, off-road vehicle use, traditional and customary use by the Miccosukee and Seminole people, the retention of private property, and oil and gas exploration.

More information about Big Cypress National Preserve can be found at "nps.gov/bicy".

The National Wildlife Refuge System promotes habitat conservation

Anne Morkill

The United States Fish and Wildlife Service (USFWS) is the primary federal agency responsible for conserving, protecting, and enhancing fish and wildlife populations and their habitats nationwide. The USFWS National Wildlife Refuge System is the premier network of public lands and waters set aside for wildlife conservation in the world.

Today, nearly 400,000 km^2 (154,000 mi^2) in more than 540 National Wildlife Refuges span every state and territory, providing important habitat for native plants and many species of mammals, birds, fish, amphibians, reptiles, and insects and other invertebrates. They also play a vital role in the recovery of threatened and endangered species.

M. Wisniewski

Library of Congress

Harvesting of feathers at the turn of the 20th Century for fashionable hats decimated wading bird populations.

There are 13 National Wildlife Refuges in south Florida (i.e., south of Charlotte Harbor and Martin County). The creation of wildlife refuges parallels the history of Florida, from early resource exploitation to rapid development and land protection. Today, these refuges continue to play an important role in the conservation of unique environments in Florida. Refuges are maintained as close to their natural conditions as possible in order to provide undisturbed habitat for native fish, wildlife, and plants. Management activities include inventory and monitoring, prescribed burning, exotic species control, and scientific research. Most refuges are open to recreational activities that are compatible with wildlife.

Early 20th century

During the late 1800s, millions of birds were harvested to use their feathers to decorate fashionable ladies' hats. In 1886, noted ornithologist Frank Chapman counted more than 500 women's hats in a single day on the streets of Manhattan decorated either with whole specimens or feathers of 40 native species of birds. By the early 1900s, the plume feather trading industry had become a very lucrative business. An ounce of bird feathers was worth $32 at that time, making them worth twice the price of gold. The hunting of adult birds for their feathers also meant abandoned nests and destroyed eggs, resulting in widespread destruction of nesting colonies of snowy egrets, herons, pelicans, and other birds across south Florida.

This wasteful exploitation of birds led President Theodore Roosevelt to begin the legacy of setting aside lands and waters dedicated to conserving wildlife. In 1908, President Roosevelt created several refuges in south Florida as preserves and breeding grounds for colonial nesting birds and other wildlife: Island Bay National Wildlife Refuge (NWR), Matlacha Pass NWR and Pine Island NWR in the Charlotte Harbor area, and Key West NWR in the Florida Keys.

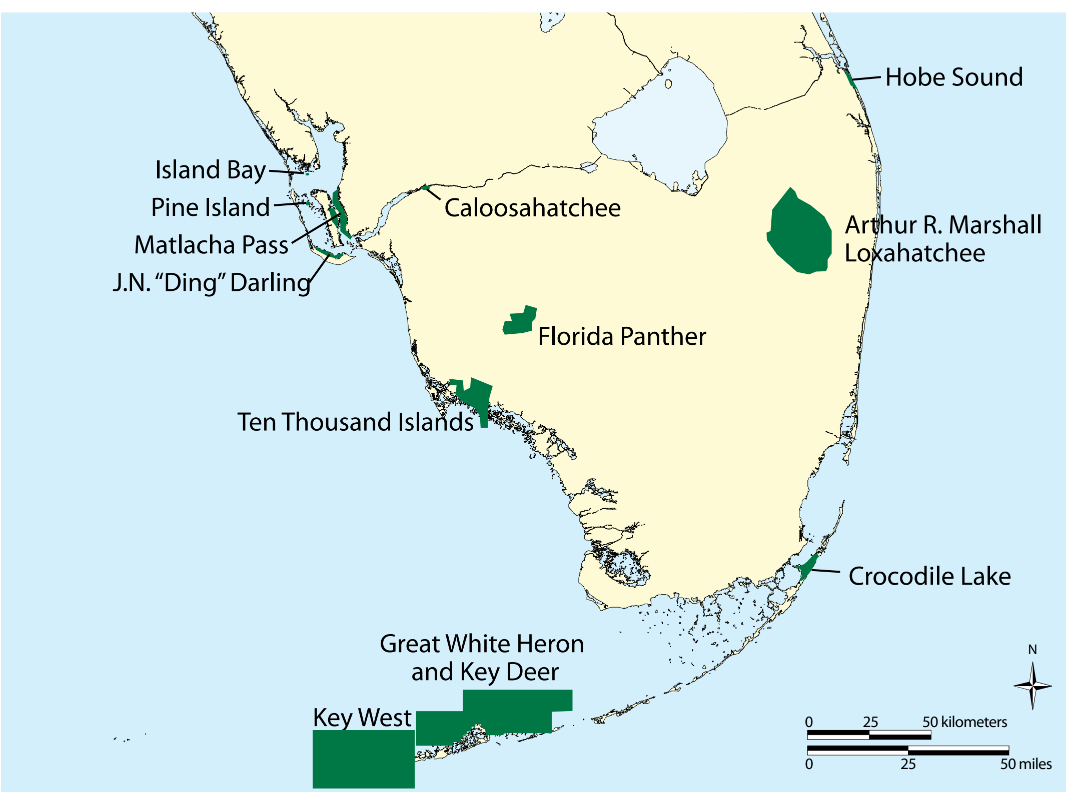
Later, Caloosahatchee NWR (1920), Great White Heron NWR (1938), and J.N. "Ding" Darling NWR (1945) were set aside to preserve intact segments of the mangrove ecosystem and nearshore habitats consisting of open water, seagrass beds, mud flats, tidal creeks, and mangrove islands that support a rich diversity of fish and wildlife. Several endangered and threatened species benefit from the protected habitats, including piping plover, roseate tern, wood stork, sea turtles, and manatee.

The 1950s to today

In subsequent decades, during a period of rapid development in coastal Florida, public awareness grew about the plight of wildlife and the loss of native habitats and several more refuges were established.

Arthur R. Marshall Loxahatchee NWR

The Arthur R. Marshall Loxahatchee NWR was established in 1951 to protect a portion of the northern Everglades on the western edge of the rapidly growing Palm Beach area. The refuge contains one of three Water Conservation Areas in



There are 13 National Wildlife Refuges in south Florida (south of Charlotte Harbor and Martin County).

south Florida and is maintained to provide water storage and flood control, as well as habitat for native fish and wildlife populations.

Key Deer NWR

This refuge was established in 1957 to protect Key deer and other unique wildlife resources in the Lower Florida Keys. By the time the refuge was established, the Key deer was nearing extinction with less than 50 deer remaining as a result of uncontrolled hunting. Habitat acquisition and law enforcement efforts have allowed the deer population to increase and stabilize. This refuge preserves diverse habitats, most notably the globally imperiled pine rockland, tropical hardwood hammock, and mangrove forests. In addition to the Key deer, the refuge provides habitat for several animal and plant species that are found only in the Florida Keys, including the Lower Keys marsh rabbit, Key tree cactus, and Big Pine partridge pea.

W.L. Kruczynski - EPA

Hunting drove Key deer to near extinction.

Hobe Sound NWR

Hobe Sound is a coastal refuge which was set aside in 1969 to protect some of the most productive sea turtle nesting habitat in the United States. The refuge also preserves sand pine scrub forest, a unique ecosystem that has been mostly lost to development in Florida. The coastal sand dunes, mangrove, and forest habitats in the refuge provide for a diversity of mammals, amphibians, and reptiles, including the Florida mouse, bobcat, gray fox, and Eastern indigo snake.

Crocodile Lake NWR

In 1980, Crocodile Lake NWR was established on north Key Largo to preserve critical habitat for the American crocodile. The refuge supports nearly 25% of the existing American crocodile population and is one of only three areas in the United States that provides nesting habitat for the species. In addition to mangrove wetlands, the refuge contains the largest remaining intact tract of tropical hardwood hammock forest containing more than 120 native species of trees and shrubs of tropical origin. The forest provides habitat to several endangered species, including the Key Largo woodrat, Key Largo cotton mouse, Schaus swallowtail butterfly, and Stock Island tree snail.

Florida Panther NWR

This NWR was created in 1989 to protect the endangered Florida panther and its habitat. The refuge is located within the core of the Florida panther distribution, centered within the Big Cypress Basin in southwest Florida. The refuge contains a diverse mix of pine forests, cypress domes and strands, wet prairies, hardwood hammocks, and lakes. In addition to the panther, many other species of mammals, birds, and reptiles are found in and around the refuge, including the Florida black bear, alligator, wood stork, limpkin, swallow-tailed kite, Everglades mink, and Big Cypress fox squirrel.

Ten Thousand Islands NWR

Set aside for protection in 1996, this refuge is part of the largest continuous expanse of mangrove forest in North America. Seagrass beds and mangroves serve as vital nursery areas for marine fish, and approximately 200 species of fish have been documented in the area. More than 189 species of birds use the refuge at some time during the year.

Coastal and Aquatic Managed Areas and Aquatic Preserves protect important habitats

Stephanie Leeds and Renee Wilson

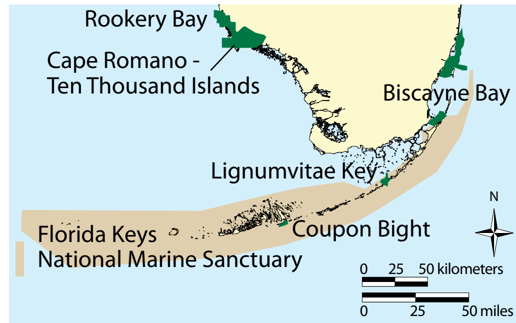
The extensive coastline and abundant marine resources in Florida have made this state not only a vacation destination for visitors but also home to millions of residents and businesses that benefit from the presence of these resources. The $53 billion tourism industry and coastal economy depend on clean water, a myriad of diverse aquatic habitats, world-class beaches, coral reefs, and wildlife.

In 1975, the Florida Legislature enacted the Florida Aquatic Preserve Act, providing critical protection for special areas. Salt marshes, seagrass meadows, coral reefs, tidal flats, mangrove forests, spring-fed rivers, and freshwater marshes are among the many habitats protected under this successful program. Currently, the Florida Department of Environmental Protection Office of Coastal and Aquatic Managed Areas oversees the management of more than 1.6 million hectares (4 million acres) of the most biologically valuable submerged lands and coastal uplands in the state. These valuable habitats are protected within three National Estuarine Research Reserves, the Florida Keys National Marine Sanctuary, the Coral Reef Conservation Program, and 41 Aquatic Preserves.

In addition to the Florida Keys National Marine Sanctuary, co-managed with the National Oceanic and Atmospheric Administration, the Office of Coastal and Aquatic Managed Areas currently manages six preserves in south Florida:

Estero Bay Aquatic Preserve in Lee County was designated in 1966 as the first aquatic preserve and is a productive estuary that supports a diverse array of aquatic and avian life.

Rookery Bay and Cape Romano – Ten Thousand Islands Aquatic Preserves in Collier County consist of fringing mangroves, mangrove islands, oyster bars, seagrass beds, and salt marshes that provide habitat for more than 200 species of fish, 150 species of birds, and plentiful other wildlife, including the endangered West Indian manatee, least tern, and loggerhead sea turtle.



Location of areas managed by the Florida Department of Environmental Protection Office of Coastal and Aquatic Managed Areas in south Florida.

Biscayne Bay Aquatic Preserve is divided geographically between Miami-Dade County and Monroe County and shares the Bay with Biscayne National Park. This Preserve supports Johnson's seagrass, a threatened species found only in southeast Florida. Manatees inhabit the Bay and are often observed in the winter as they gather in warm waters.

Lignumvitae Key and Coupon Bight Aquatic Preserves in Monroe County encompass seagrass meadows, hardbottom communities, mangroves, and patch reefs. Wading birds can often be observed feeding in the shallow waters and roosting in mangroves in both preserves. The endangered Key deer is a frequent visitor to the mangrove habitat at Coupon Bight that offers cover and foraging habitats.

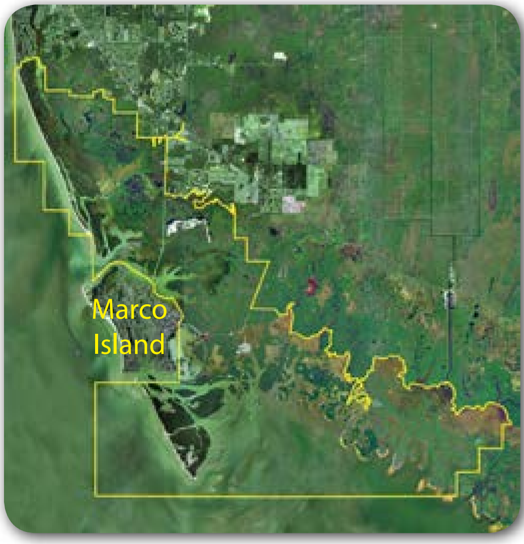
Protection and management of preserves provides habitats for wildlife and educational opportunities for students, teachers, and scientists looking for a hands-on approach to learning. For more information, visit "dep.state.fl.us/ coastal".

Rookery Bay National Estuarine Research Reserve contains relatively undisturbed mangrove estuaries

Renee Wilson

An amazing world exists within the pristine, mangrove-fringed waterways, uplands, and freshwater wetland habitats of the Rookery Bay National Estuarine Research Reserve. Found only a few miles away from one of the fastest growing metropolitan areas in the country, the reserve is located between Naples and Everglades National Park and encompasses roughly 445 km^2 (172 mi^2) of coastal lands and waters along the Gulf of Mexico.

The Reserve represents one of the few remaining relatively pristine mangrove estuaries in the United States. Growing from a grassroots effort, the core lands of Rookery Bay were designated as a Research Reserve in 1982. The Reserve is managed by the Florida Department of Environmental Protection Office of Coastal and Aquatic Managed Areas, in cooperation with the National Oceanic and Atmospheric Administration.



Rookery Bay National Estuarine Research Reserve

The boundaries of Rookery Bay National Estuarine Research Reserve encompass 445 km^2 (172 mi^2) of pristine mangrove forests, beaches, uplands, and protected waters of Rookery Bay. The protected area surrounds densely populated Marco Island and supports more than 450 species of plants, 220 species of fish, and 200 species of birds.

The mission of the Reserve is to promote informed coastal decisions through research, stewardship, and education. Exploration of this national treasure can begin with a visit to the Rookery Bay Environmental Learning Center. The multimillion dollar, state-of-the-art Center highlights the diversity of plants and animals found within the protected area of the Reserve, which serves as habitat for more than 450 species of plants, 227 species of fish, and 200 species of birds.

C. Anderson - USFWS

The least tern, a beach nesting bird, is heavily affected by loss of coastal habitat. In cooperation with Florida Fish and Wildlife Conservation Commission, the Reserve annually closes off beach areas where least terns are nesting.

Because of its value to the scientific community, the Reserve maintains a balance of compatible public use and protection, encouraging passive or low impact activities. With the exception of fishing and commercial shellfish harvest, all plants and animals within the Reserve are protected.

To help ensure long-term protection of habitats that provide refuge for the amazing diversity of native coastal wildlife, reserve staff work in partnership with other agencies, the local community, and volunteers. Research and monitoring, resource management, education and outreach, and professional training help facilitate a better understanding of this ecosystem and ways to help sustain a healthy estuary for years to come.

Shallow water fishing is popular in Florida Bay and nearshore coastal waters

Jack Teague

The breadth and diversity of fisheries in south Florida, particularly in the Florida Keys, make it one of the premier destinations for anglers in the continental United States. Although perhaps not as prolific as historically documented, no other locale offers fishing enthusiasts opportunities to encounter such a wide array of species and habitats. The presence of targeted species is correlated to seasonal patterns of movement and, in the short term, tidal phase and ambient water temperature, which affects food sources and comfort zones.

Inshore fishing includes flats, backcounty, and reef fishing and is loosely defined as fishing within 8 – 10 kilometers (5 – 6 miles) from the edge of land, out to and including the bank reef tract. The shallowest areas near to shore are known as "flats" or "tidal flats," which are mixtures of seagrass and hardbottom communities. Flats fishermen seek out bonefish, permit, tarpon, barracuda, and sharks. Water clarity on shallow flats is exceptional and enables sight casting to these animals, perhaps the most technically challenging form of fishing. Flats fishing is predominantly catch and release.

Backcountry fishing is defined as inshore fishing around uninhabited mangrove islands and tidal channels, like those found on the Gulf side of the Keys. Other backcountry options include the shallows of Florida Bay, Everglades National Park, and tidal channels and shorelines in the Ten Thousand Islands. Snook, tarpon, redfish, speckled trout, gray snapper, and sharks are common backcountry catches. Other inshore options include bay and wreck fishing, such as in Biscayne Bay and wrecks off Marco Island and other locations in the shallow Gulf of Mexico.


J. Teague - Finatic Charters

Typical "skinny water" flats fishing skiff used in south Florida.

J. Teague - Finatic Charters

Mutton snapper caught on a patch reef off of Key West is fine table fare.

As water depth increases with distance from the shallows, coral communities begin to dominate the sea bottom. Within the boundary created by the tidal flats and offshore bank reef on the Atlantic side of the Keys are numerous isolated coral communities often referred to as "patch" reefs. The bank and patch reefs, as well as artificial reefs, provide excellent structure that provides habitat for several species of grouper and snapper that are prized by anglers as food fish. Predators, such as sharks and barracudas, are also common inhabitants of these areas. Seasonally, members of the mackerel family visit patch and bank reefs, and pelagic species, such as little tunny and sailfish, visit the bank reef.

Healthy fisheries in south Florida are directly related to preservation of each habitat type that supports various phases of fish life cycles (e.g., seagrass, mangroves, marshes, hardbottom, coral reefs). Habitat loss and degradation has resulted in diminished catch per effort ratios compared to historical catches. The importance of preservation of habitat to the sustenance of inshore fishing cannot be overstated.

Responsible fishing practices and informed management are required to sustain south Florida's world-class offshore fishery

Jack Teague

The position of south Florida as the tip of a geographical phalanx jutting out into the confluence of Caribbean, Gulf of Mexico, and Atlantic Ocean subtropical waters places it directly in the migratory routes of many pelagic species of fish. It is the legendary territory of blue water, deep-sea fishing. The Florida Current flows constantly through the corridor known as the Florida Straits, creating currents and thermal edges that control the location of forage fish and floating structure, such as Sargasso weed and flotsam. The location of the shoreward edge of the Florida Current varies; generally, it is about 16 kilometers (10 miles) off Key West and 3 – 5 km (2 – 3 mi) off Fort Lauderdale. At 32 – 40 km (20 – 25 mi) out, the continental shelf drops away, creating bathymetric features that influence ocean currents as well.

J. Teague - Finatic Charters

Sailfish are a popular game fish in offshore waters.

Anglers ply these waters seeking popular big game fish, such as blue marlin, sailfish, dolphin fish (Mahi-Mahi), wahoo, tuna, and swordfish. The presence of their quarry is often indicated by activity on the ocean surface, such as the presence of diving seabirds, particularly frigates and terns, and sprays of bait fish leaping from the water in an attempt to escape death from below. The tenure of the big game species in south Florida is typically seasonal in nature, though occasional members of any of the species may be caught year-round. Fish targeted during fall/winter include sailfish, kingfish, wahoo, and tuna. During spring/summer, dolphin fish usually dominate the offshore catch, but marlin, tuna, sailfish, and wahoo are also regularly caught.

NOAA

Floating Sargasso weed is essential nursery and foraging habitat for big game fish, such as dolphin fish and sailfish.

The floating seaweeds, *Sargassum natans* and *Sargassum fluitans* (collectively called Sargasso weed), are commonly found offshore and can cover large areas of the ocean. Generally, weed lines are concentrated along the edges of currents and eddies. Sargasso weed harbors a diverse community of sea life, consisting of the floating live weed, the myriad tiny sea creatures living in its clusters, and successive orders of predators attracted to the forage. The Sargasso weed is the essential foundation of the food web and nursery for a healthy pelagic fishery.

Sargasso weed has commercial and industrial uses and has been harvested for its economic value without concern for the creatures living within and beneath the mass. *Sargassum* is subject to the whim of current and wind; it passes through the waters of several political boundaries, so its protection and preservation beyond south Florida must be a national and multinational effort to preclude serious detrimental collateral impacts to pelagic fish species.

No-take marine reserves are an important management strategy for exploited reef fish stocks

Jerald S. Ault and James A. Bohnsack

The timeless appeal of the Florida Keys has attracted an ever-increasing number of residents and visitors, which have increased human pressures on the natural resources. The Florida Keys is one of the most significant, but most stressed, marine ecosystems in the nation. Rapid declines of historically productive fishery resources and degradation of coral reef habitats have spurred development and implementation of innovative strategies to manage human activities and satisfy multiple, often conflicting, user groups. Determining the efficacy of different management approaches is one of the most critical marine resource management problems and a unique challenge for science-based resource management.

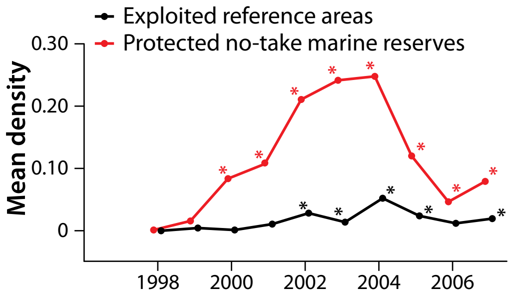
NOAA

A network of no-take marine reserves was created between Miami and the Dry Tortugas to provide fishery habitat.

A highly touted management strategy involves the design and creation of "no-take" marine reserves (NTMRs) as the means of protecting coral reef habitats and rebuilding declining fisheries. Extractive uses, such as hook-and-line and spear fishing, are prohibited in NTMRs. On July 1, 1997, the Florida Keys National Marine Sanctuary (FKNMS) established a network of NTMRs along the Florida Keys Reef Tract between Miami and Key West. The network was comprised of 18 Sanctuary Preservation Areas, four Special Use Areas, and a larger Western Sambo Ecological Reserve. The network was later expanded by establishing much larger NTMRs in the Tortugas in 2001 and 2007.

Recent research has focused on determining the ability of NTMRs to meet conservation goals by comparing population trends for key exploited and nonexploited reef species in areas closed and open to fishing. Theory predicts increased density, abundance, and size of exploited reef fish species within the NTMRs and benefits over time to surrounding fished populations by "spillover" (fish swimming across the NTMR boundary) or by increased reproduction from more abundant and larger fish within the NTMRs. The time required to observe these changes depends on population characteristics of each species. To test the theory, 30 years of reef fish data (1979 – 2009) were collected for more than 280 species using intensive underwater visual reef fish surveys. The survey design incorporated statistical sampling models to provide accurate and precise spatial data that relate key reef fish population and community assemblages to specific habitats and management zones. Principal survey statistics included species composition, frequency of occurrence, mean density, species richness, and total population abundance by size category ranging from juvenile recruits to mature and exploited size classes.

Temporal changes in population and communities were analyzed from data collected within and outside NTMRs after FKNMS reserves were established in 1997. Over the next decade, mean densities of exploited reef fish species generally increased significantly in reserves as predicted by marine reserve theory. Mean density of black grouper (*Mycteroperca*



Comparison of black grouper density trends in protected no-take marine reserves and Western Sambo Ecological Reserve (red line) and exploited reference areas (black line). Asterisks denote significantly different densities from the "no significant change" projection.

bonaci), for example, increased rapidly after establishing reserves. Starting in 2000, mean densities had increased significantly above the baseline and remained there throughout the remainder of the study. By 2004, mean abundance had increased approximately 32-fold above the pre-reserve baseline level. The average increase during the study was 15-fold above the baseline. Mean densities in NTMRs declined significantly in 2005 and again in 2006 following intense hurricane seasons. Overall, however, the densities in NTMRs remained significantly higher than areas open to fishing. For comparison, mean black grouper density in fished areas increased significantly above the baseline in 2002, 2004, 2005, and 2007, but the increase was considerably less than what was observed in NTMRs. Black grouper density was hundreds of times higher in NTMRs than in fished areas from 2000 – 2007.

Visual reef fish surveys were also performed to assess reef fish population changes before and after the establishment of NTMRs in the Tortugas. The FKNMS established 391 km^2 (151 mi^2) Tortugas Ecological Reserve in 2001 in the westernmost area of the Sanctuary. In January 2007, the National Park Service established a 158 km^2 (61 mi^2) no-take Research Natural Area in Dry Tortugas National Park that provided a shallow water complement to the deeper Tortugas Ecological Reserve. Total number of fish species (267 species) and composition remained stable within the Tortugas survey domain between the 1999 – 2000 baseline and 2008. Reef fish diversity was highest in rugose habitats with high vertical relief. Domain-wide increases in abundance of several exploited and nonexploited species were observed, while no declines were detected. In the Tortugas Bank NTMR, some species showed significantly greater abundance and shifts in length composition toward a higher proportion of larger exploitable sized animals in 2008 compared to 1999 – 2000. Consistent with marine reserve theory, no declines in abundance of exploited species were detected within the reserves, though both increases and declines in nontarget species were observed.

Other factors besides NTMRs likely influenced density trends in the Florida Keys. More restrictive fishing regulations, for example, may have also influenced observed increases in abundance and average size of exploited species. Physical disturbance from hurricanes and tropical storms was prominent in the decade following the establishment of FKNMS NTMRs. A total of nine storm events impacted the Florida Keys over 4 years, including Hurricane Georges and Tropical Storm Mitch in 1998; Hurricane Irene in 1999; Hurricane Charlie and Tropical Storm Ivan in 2004; and Hurricanes Dennis, Katrina, Rita, and Wilma in 2005.

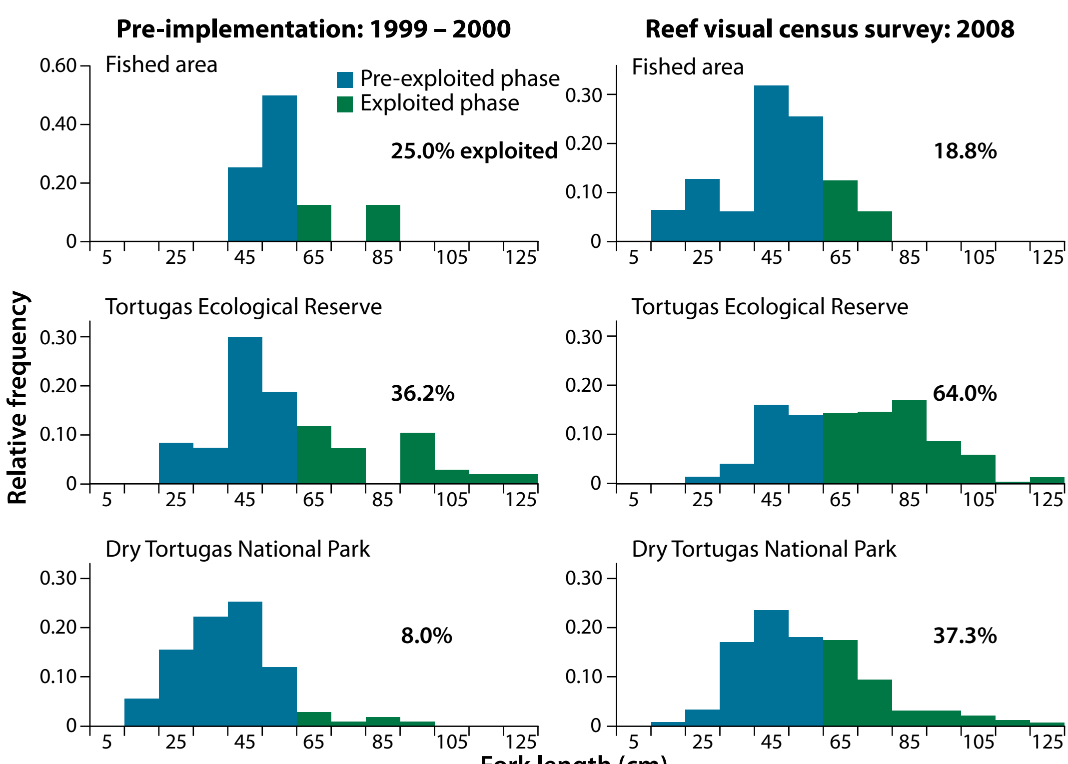
J. Luo - UM/RSMAS

A diver-based reef fish visual census is conducted annually in marine reserves and fished areas to determine the effects of protection on fish composition, abundance, and size structure.

Human Connections

Since the only factor directly changed by marine reserves was no fishing in NTMR zones, the magnitude and pace of the density increases in reserves indicate that fishing has a strong influence on exploited reef fish populations in the FKNMS. Other environmental concerns, such as water quality, may be less important.

NTMRs are expected to provide tangible long-term benefits for protection of marine resources in the Dry Tortugas National Park and the FKNMS. Reserves eventually should benefit recreational and commercial fishers by reducing the chances of overfishing and by enhancing reproduction to ensure a supply of replacement recruits for fishing areas. These highly protected reserves will also advance science, serving as reference sites to distinguish between natural and human-induced changes to the Florida Keys ecosystem. In order to meet legislative mandates, university, federal, and state personnel conduct comprehensive research assessment cruises to monitor fishery and habitat resource changes and assess the effectiveness of NTMR designs and other management regulations. Research to date indicates that FKNMS marine reserves have compelling beneficial impacts on sustaining marine fisheries and conserving biodiversity in the Florida Keys. Although the recovery process in reserves is still early, results are encouraging and suggest that combining fishing regulations with large NTMRs may be the most effective way to protect coral reef ecosystems, reduce risks of stock collapse, and restore depleted stocks while maintaining sustainable economic and social benefits.



These graphs depict the response of black grouper population size structures to no-take marine reserve protection. Baseline size estimates (pre-implementation fork length) were taken during 1999 – 2000. The top two graphs represent areas where fishing is allowed, and in those fished areas the number of black grouper capable of being caught (green bars) decreased from 25% to 18%. However, in the two managed areas, Tortugas Ecological Reserve and Dry Tortugas National Park, the large size class numbers increased significantly from pre-implementation levels.

Sound science is required for adaptively managing coral reefs

Steven L. Miller, William F. Precht, and Struan R. Smith

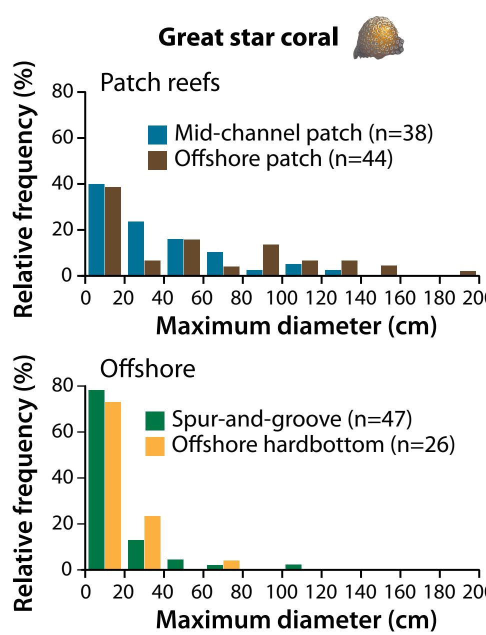
Recovery of coral populations is a priority for resource managers because so much coral has been lost in recent times. An understanding of the population dynamics of coral reefs, including factors that affect coral decline and reproductive success, are critical to ascertain and evaluate methods for managing (i.e., through adaptive management) the restoration of coral diversity and abundance on Florida coral reefs. For recovery of populations to occur, the stressors responsible for causing the declines must be reduced or eliminated. Factors causing the decline of corals in the Keys do not appear to affect coral recruitment in ways that differ from what is currently occurring throughout the Caribbean basin.

Coral decline

Loss of corals is typically reported as a decrease in percent cover, which is a decline in the portion of the bottom that is covered by living coral. Between 1996 – 2002, coral cover decreased by over 50% at selected spur-and-groove bank reefs in the Florida Keys. Loss of coral is thought to be caused by consecutive mass bleaching events (e.g., 1996 and 1997) and hurricanes.

Coral cover includes the following components: recruitment of new corals, growth, and mortality. A change in any of those components will result in a change in percent cover. The processes affecting coral survival can vary depending on habitats and species, and among different size classes of corals. Thus, simply reporting percent cover does not adequately characterize important parameters of coral populations. For example, similar estimates of percent cover would be measured from a reef with a high density of small colonies and a reef with low densities of mostly large colonies. But, the reefs are very different in terms of ecological structure and function. Thus, complexities in populations of corals are not explained by estimates of percent coral cover alone.

Measurements of individual coral colonies to determine coral size-class structure reflect the recent history of juvenile recruitment, growth, and mortality in the population. However, it too is not the whole story. A population without large corals may reflect historical events of mortality from disease or natural physical and biological processes that prevent corals from getting large in a particular habitat. Frequent and repetitive sampling is required to identify cause and effect relationships that explain factors causing their decline.



Size classes of great star coral on mid-channel and offshore patch reefs (top) and offshore high relief spur-and-groove and low relief hardbottom habitats (bottom). Patch reefs and offshore habitats both show a typical distribution, with most colonies in the smallest size classes and fewer in the largest size classes. Compared to offshore habitats, however, many more corals on patch reefs survive to medium and larger size classes. Numbers of colonies (n) sampled in each habitat are shown.

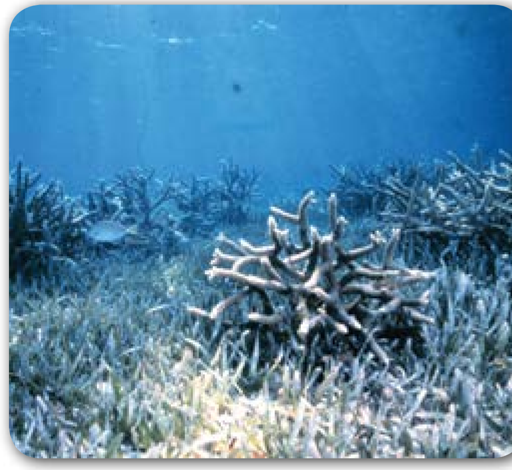
Importance of physical and genetic connectivity

Coral reef management, including design and establishment of Marine Protected Areas, is based on the premise that individual reefs are connected, to varying degrees, by patterns of water flow and exchange of biological materials (e.g., adults, juveniles, larvae). Because of coral larval dispersal, reefs linked to each other by prevailing currents can help maintain biodiversity and facilitate recovery of degraded coral reefs.

Elkhorn coral (*Acropora palmata*) and staghorn coral (*Acropora cervicornis*) have declined approximately 95% in the Florida Keys, largely due to disease. If recovery of these species is to occur, it must come from local remnant populations or from more distant populations through larval dispersal. Until recently, scientists did not know if sufficient numbers of individuals remain locally to successfully reproduce consistently, or if larval transport from distant healthy "rescue reefs" is required to repopulate degraded sites. Genetic fingerprinting on staghorn coral has revealed two important findings:

1. Florida staghorn coral populations are not genetically depauperate; and,
2. Substantial exchange occurs among populations throughout the Keys, covering a distance of over 200 kilometers (124 miles), under a wide range of environmental conditions.

Thus, significant genetic variation remains in the remnant populations of staghorn coral throughout the Florida Keys. This was a concern because low genetic variability represents a barrier to successful reproduction; fragmented clones cannot sexually reproduce with themselves. The level of genetic diversity within the species in the Keys is a hopeful sign that some level of resilience exists, and that the ability to adapt to environmental change is possible. Indeed, it was recently shown that 6% of staghorn coral individuals are resistant to white-band disease, clearly demonstrating that the genetic makeup of the population is important.


FKNMS

The genetic structure of staghorn coral populations in the Florida Keys suggests restricted gene flow between Florida and the Caribbean. Therefore, recovery of the south Florida population is largely dependent on successful larval recruitment from local adult populations.

Genetic differences were not observed between Upper and Lower Keys staghorn coral populations, suggesting that reefs throughout the Keys are connected and not isolated from each other; they exchange larvae sufficiently to maintain substantial genetic variability. Furthermore, larval recruitment appears to be low from other populations in the Caribbean. That is, genetic exchange does not appear to regularly occur across the large expanses of the Caribbean and into Florida. Regional genetic groups are sorted into Western Caribbean, Eastern Caribbean, Greater Bahamas, and Florida populations. This means that larval production and retention within the Florida Keys is critically important to the recovery of the species in the Keys. Therefore, the Keys should be treated as a distinct area for conservation, where recovery of staghorn coral will depend on successful recruitment from existing local adult populations. Coupled with the ability of staghorn coral to reproduce asexually by fragmentation and grow rapidly (up to 10 centimeters [4 inches] per year), there is reason to be optimistic about Florida staghorn coral recovery.

Coral reef conservation and management must address multiple stressors

William F. Precht and Steven L. Miller

South Florida is subject to a host of conditions unfavorable to prolific reef development, given its location at the northern limit of coral reef growth in the western Atlantic. In fact, Florida is fortunate to have reefs at all because of the multiple stressors that impact them. Disease epidemics, coral bleaching events, extreme weather conditions including hurricanes and cold fronts, as well as the average position of the Florida Current affect the location, extent, and health of reefs in Florida. In addition to these natural stressors, there are a host of anthropogenic stressors that affect the way south Florida coral reefs look and function. These include, but are not limited to, overfishing, nutrient loading, sedimentation associated with coastal activities such as dredging, various forms of pollution related to poor watershed management, harvesting of reef invertebrates, trampling by tourists and divers, and the destruction and devastation caused by ship anchors and groundings. The degraded condition of many coral reefs in Florida justifies the need for immediate protection. Many of the anthropogenic causes of coral decline can be reduced, minimized, or avoided by implementing local, scientifically-based management programs.

Although hurricanes and cold fronts are clearly naturally occurring events, the causes of global climate change, coral disease, and increasing severity of El Niño Southern Oscillation-related warming events have been linked to human activities, in part through the emission of greenhouse gases. It is imperative that resource managers and policy makers directly address the broad range of factors that have devastated coral populations and hinder their recovery. Understanding the biological, chemical, and physical aspects of complex coral ecosystems is critical for successful management. However, people and communities rely on these resources, so it is often the social, economic, or political aspects of coral reef management that influence decisions. To be effective, coral reef management strategies should engage and actively involve communities.

Resolving the crisis of declining coral reefs will require tandem action on local, regional, and global levels by coral reef scientists, policy makers, managers, nongovernmental organizations, and the public. Accordingly, we must combine local management strategies with regional intergovernmental policies and ultimately global stewardship, if we are to make progress in efforts to restore and maintain Florida coral reefs.

Stressors to Florida coral reefs

Natural stressors include:

- Coral disease and bleaching;
- Extreme weather conditions;
- Position of the Gulf Stream;
- Predation; and
- Bioerosion.

Anthropogenic stressors include:

- Overfishing;
- Eutrophication;
- Sedimentation;
- Harvesting;
- Diver impacts; and
- Anchoring and grounding.

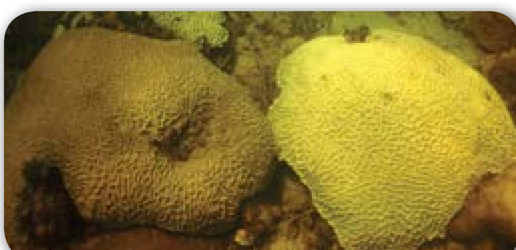
D. Burdick - NOAA

Florida coral reefs are subject to multiple natural and anthropogenic stressors, including impacts from divers.

The Florida Reef Resilience Program develops science-based strategies for coral management

Chris Bergh

Resilience is the ability to resist, recover from, or adapt to stress. Coral reef resilience is the ability of the ecosystem to recover from natural or anthropogenic disturbances. Coral resilience is often measured as the ability of coral colonies to recover after bleaching or other stressors. Some coral colonies are more resilient to stressors than others and can either resist bleaching completely or tolerate and survive bleaching, whereas a colony that is not resilient will perish. At the scale of entire reefs, or even at greater geographic scales, resilience may allow stony coral populations to recover after a portion of the coral population is lost due to bleaching or other stressors that cause widespread coral mortality.



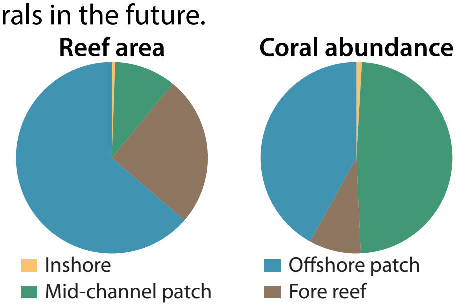
M. Johnson - TNC

Corals growing side by side, one bleached and one resilient to bleaching. If resilient corals can be found and protected, they may facilitate reef recovery following stressful events.

Reef resilience can also be defined as the ability of a coral reef ecosystem to resist "phase shifting", which is a change in species composition. When stressed by natural or anthropogenic disturbances, coral reefs can shift from a coral-dominated to a macroalgae-dominated system. Drivers of phase shifts on coral reefs include water quality degradation, bleaching events, and overfishing. Individual stressors taken together can be synergistic. For example, once herbivorous fish populations are decreased, resultant algal growth can outcompete corals weakened by bleaching or other diseases.

In 2005, a consortium of reef managers, scientists, conservation organizations, and reef users initiated the Florida Reef Resilience Program to improve understanding of reef resilience and develop resilience-based management strategies for the Florida Keys and southeast Florida. In order to identify coral species, reefs, and general areas of the reef ecosystem that may be resilient to bleaching and other stresses, the Florida Reef Resilience Program conducts an annual Disturbance Response Monitoring effort during the hottest period of each summer. Coral species diversity, and coral colony size and condition, including presence of bleaching, diseases, and recent mortality, are measured.

Analysis of the monitoring data from 2005 – 2007 indicates that no subregions of the reef ecosystem are immune to bleaching. The analysis also enables comparisons of the amount of reef habitat in a given area with the number of coral colonies found in that area. In Biscayne National Park and the Florida Keys, for example, there are disproportionately large numbers of corals in the relatively small area of mid-channel reefs. By minimizing human activities that damage resilient corals on mid-channel reefs, managers may provide protection of areas that could serve as critical sources of corals in the future.



Reef area and estimated coral abundance for Biscayne Bay and the Keys. Mid-channel reefs (green) make up a relatively small percentage (10.4%) of total reef area (left), but contain a relatively large percentage (48.4%) of all the coral colonies in the geographic area (right).

Coral reef mitigation in southeast Florida

David S. Gilliam and Jocelyn L. Karazsia

The Southeast Florida Reef System extends over 145 kilometers (90 miles) north of the Florida Keys, in Miami-Dade, Broward, Palm Beach, and Martin Counties. The reefs in this area generally occur in one to three shore-parallel terraces separated by sand habitats. Southeast Florida reefs are located offshore of a highly urbanized coast, which results in many physical stresses on the reefs. Impacts to coral reefs in this area can be caused by a variety of activities, including marine construction, fiber optic cables, beach renourishment, channel dredging, and major vessel groundings.

Marine construction activities require authorization from local, state, and/or federal regulatory entities. The permitting process can result in a compensatory mitigation requirement to offset unavoidable impacts to coral reefs. Compensatory mitigation is considered an option only after a thorough and exhaustive assessment of project alternatives that may be less environmentally damaging has been completed. Additionally, it is assumed that sequential mitigation (i.e., first, avoid; second, minimize; third, compensatory mitigation) has been duly considered to the point that all impacts to reef are "unavoidable". Mitigation amounts are determined through the use of a functional assessment, such as Habitat Equivalency Analysis or Florida Uniform Mitigation Assessment Method.

D.S. Gilliam - NSU

A limestone boulder mitigation reef.

D.S. Gilliam - NSU

Mitigation reefs can also serve as coral nurseries to aid future restoration activities.

Historically, mitigation through the construction of mitigation reefs has been the preferred mitigation option for southeast Florida. If constructed properly, a mitigation reef can provide the necessary framework for the colonization of corals, sponges, algae, and other reef-associated species. The goal of a mitigation reef should be to replicate the functional attributes of an impacted reef, such as coral cover and species richness.

Mitigation reefs must be monitored to determine if they provide equivalent ecological services and functions of natural reefs. However, there are insufficient long-term data to show that mitigation reefs are replacing the lost services from natural reefs that have been impacted. Reef managers and scientists are currently exploring alternative reef mitigation options because it is thought that the Southeast Florida Reef System has a limited need for artificial and mitigation reef substrate. Evaluation of alternative mitigation options requires examination of the needs of the entire reef ecosystem and could include actions to lessen pollutant loads into coastal waters or to abate other threats to reefs, such as anchoring, overfishing, and climate change. In addition, research is needed to increase our understanding of the reef system and to identify ways to improve the overall condition of the Southeast Florida Reef System.

Landscape-scale approaches show much promise for future coral reef restoration projects

William F. Precht, William Goodwin, and Ken Nedimyer

The specific goal of coral reef restoration is to restore the ecological functions of the reef ecosystem. However, most historical restoration projects in south Florida have concentrated on reconstructing the damaged underlying reef structure at injured sites with little emphasis on reestablishing benthic community attributes. In the past, reef restoration consisted primarily of using concrete and/or limestone boulders to stabilize the damaged substrate. Today, a holistic landscape-scale approach to restoration, including nursery coral transplantations, is accelerating the reestablishment of biodiversity in damaged areas. A landscape approach can also ensure that some stressors to the reef ecosystem are removed or accounted for, and that critical coral species and some ecological processes are introduced to the injured site.

K. Nedimyer - CRF

These cultured staghorn corals were transplanted to a restoration site in the Upper Keys to ensure that critical species are successfully introduced to the restored reef.

K. Nedimyer - CRF

K. Nedimyer - CRF

Successful establishment of offshore coral reef nurseries have facilitated landscape restoration projects at damaged coral reef sites. Transplanted corals accelerate establishment of biodiversity and ecological functions at restoration sites.

In the past, transplanting corals at restoration sites has been limited by availability and health of coral transplants. However, new techniques in coral husbandry and aquaculture now allow the opportunity for transplantation of coral fragments on a landscape scale at restoration sites. In 2000, culturing of coral fragments at offshore sites was initiated with the hope of using coral transplants on a large scale to restore degraded and damaged reefs. By 2008, offshore coral nurseries had more than 2000 corals ready to transplant at restoration sites. Numerous pilot projects in the Florida Keys National Marine Sanctuary using transplanted elkhorn (*Acropora palmata*) and staghorn (*Acropora cervicornis*) corals have yielded positive results. These projects continue to grow in size and scope. Monitoring shows that transplanted corals are thriving and will accelerate full restoration of ecosystem functions. New methodologies and lessons learned from the past are forging innovative and successful coral reef restoration in south Florida.

Coral reefs impacted by groundings of large vessels can be restored

William Goodwin and William F. Precht

An important factor in initiating congressional designation of the Florida Keys National Marine Sanctuary (1990) was a succession of groundings of large ships on ecologically important coral reefs in the Florida Keys. In 1984, the freighter *Wellwood*, 122 meters (400 feet) in length, ran aground on Molasses Reef and leveled approximately 1500 m^2 (16,000 ft^2) of coral reef. In 1989, the freighter *Elpis*, 143 m (469 ft) length, ran aground on The Elbow, a spur-and-groove bank reef. Also in 1989, the *Maitland*, a 47 m (154 ft) length commercial shipping vessel, ran aground on a low relief coral shoal near Carysfort Reef. Even with sophisticated electronic navigation, charting, and depth finding, equipment malfunctions and human error still result in vessel groundings. For example, in 1994, the *Columbus Iselin*, a research vessel with state-of-the-art electronics, ran aground on the reef crest at Looe Key Reef and flattened over 300 m^2 (3200 ft^2) of shallow spur-and-groove reef structure.

The impacts of large ship groundings to coral reefs are extensive and long-lasting. If left unattended, it is not uncommon for grounding-related injuries to be visible for decades. The severity of the injury is related to size of the vessel, weather, tides, how quickly the vessel can be removed,

FKNMS

Grounding of the *Wellwood* reduced the spur-and-groove reef formation at Molasses Reef (Upper Keys) into a flat, featureless, landscape devoid of habitat value.

W. Goodwin - FKNMS

Grounding of the *Columbus Iselin* at Looe Key (Lower Keys) resulted in major damage to a large area of spur-and-groove reef structure.

and techniques used during the salvage operation. Also, attempts to "power off" the reef using the engine of the grounded vessel results in additional injury. The most serious structural damage to the reef at the *Elpis* grounding site occurred when the ship propellers excavated two large craters in the reef substrate. An excavation crater 25 m (82 ft) in diameter and 2 m (6.6 ft) deep was created by the ship propeller wash as the captain of the *Maitland* tried in vain to extricate his vessel.

The Damage Assessment, Remediation, and Restoration Program of the Sanctuary is a valuable resource protection tool to ensure that Sanctuary resources are maintained for future generations. The damage assessment and restoration process is designed to determine the scope of feasible, cost effective and timely restoration of those natural resources and services injured by an incident. The Sanctuary uses an interdisciplinary team of biologists, economists, lawyers, and resource managers to assess and recover natural resource damages from those who cause these injuries. The funds collected are then used to implement the restoration project and to monitor recovery.

Effective restoration plans for damaged coral reefs have evolved over time. The Program has designed and implemented some of the largest and most ambitious reef restoration projects in the world. In general, there are four stages to a reef restoration project:

1. Rescue damaged organisms. Broken or dislodged hard corals and other sessile reef biota are collected and temporarily relocated to a nearby site or an established nursery facility, where they remain until the reef is restored and the salvaged organisms can be reattached.
2. Manage rubble. If left loose and unconsolidated, rubble (i.e., crushed reef) can move and smother or otherwise harm unimpaired reef areas. Rubble can be moved by storm-generated waves that can "sandblast" nearby reefs. Removal of loose rubble and incorporating the pieces into replacement objects to rebuild reef structure has proven to be the most effective method of minimizing damage from rubble.
3. Restore original grade, structure, rugosity, and stability of the grounding site. Various methods of rebuilding the reef structure are utilized depending upon the size and complexity of the damaged area of reef. All involve cementing together substrate materials that mimic the reef structure and provide nooks and crannies and vertical relief.
4. Monitor. This is required to evaluate success of the restoration efforts.

The structural restoration of the *Elpis* site included placement of large limestone boulders in the excavation craters. This immediately replaced lost rugosity, stabilized remaining loose rubble, and provided a stable substrate for recolonization by hard corals and other biota. Reef replacement structures at the *Maitland* site were constructed of steel reinforced poured cement. These modules had quarried limestone boulders incorporated into their construction to add rugosity and a more natural look and were cemented in place. At the *Columbus Iselin* site, large limestone boulders were placed into the grounding scars and cemented in place; large pieces of fossil coral material salvaged from the rubble were cemented around the boulders.

At the *Wellwood* site, then Program biologist Dr. Harold Hudson designed and constructed reef replacement modules that evolved from the lessons learned from previous restoration efforts. Each module was a miniature replica of a natural coral spur and was constructed by cementing boulders on a slab base with an open center creating a cave. Twenty-two of the modules were lowered and cemented in place. Monitoring a decade after completion of the *Wellwood* project has revealed that the structures are festooned with coralline algae, sponges, gorgonians, hard corals, and other living coral reef organisms.

The Program continues to routinely monitor these and other reef restoration sites in the Sanctuary. The goal of the program is to develop and apply the best techniques for reef restoration, including propagation of nursery-grown corals, so that future restoration projects replicate as closely as possible the ecological functions, habitat quality, substrate stability, and aesthetic appeal of the natural reef prior to grounding incidents.

J. Anderson - NOAA

A limestone boulder cemented in place at the *Elpis* restoration site 10 years after placement reveals successful colonization of sponges, corals, and other reef organisms and replacement of lost habitat.

Quick efforts help restore impacts from small vessel groundings

William Goodwin, William F. Precht, and Ryan Wattam

Despite the fact that many reefs in the south Florida coral reef tract occur within the boundaries of Marine Protected Areas, the reefs continue to be impacted by groundings of vessels of all sizes, from small recreational boats to large commercial container ships. The Florida Keys National Marine Sanctuary Damage Assessment, Remediation, and Restoration Program is responsible for developing and implementing coral reef restoration plans in response to vessel groundings.

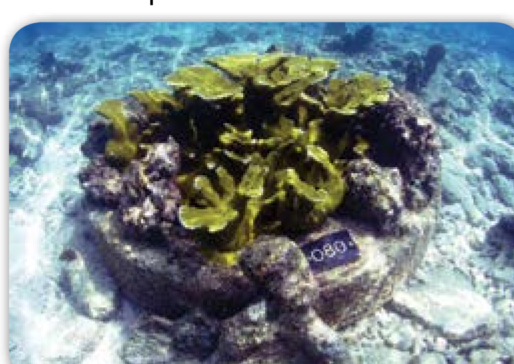
H. Bailey - FKNMS

This overturned colony of boulder star coral must be righted and cemented in place quickly to maximize its chance of survival.

Groundings of small vessels require quick emergency actions (i.e., coral reef “triage”) to limit physical and biological damage and restore reef functions. Restoration may require little more than removal of the vessel debris and bottom paint. The faster the debris is removed, the less chance that it will be moved by wave action and cause further damage. Removal and/or stabilization of loose rubble and sediment, and stabilization of structural fractures, may also be required. Timing is also critical to minimize or eliminate further damage to corals and other marine life that were broken and dislodged at the grounding site. Quickly righting and reattaching dislodged coral colonies before they are further injured or die is required to return the injured reef to its pre-grounding condition. Sometimes, living corals and nonliving reef structural framework elements that were broken, crushed, or excavated may require aggregating into a replacement structure that replicates the original in form and function.

Groundings by large-sized ships, such as commercial fishing boats and freighters, result in catastrophic impacts that require physically rebuilding the structural foundation of the reef so that the site can be restored in a time frame measured in years instead of decades or centuries. Coral reef restoration on a large scale becomes a major marine construction project that requires considerable planning, equipment, and materials and may take years to successfully implement.

Whenever a grounding of any size occurs in a National Marine Sanctuary, the National Oceanic and Atmospheric Administration (NOAA) can seek monetary damages to cover response, injury and damage assessment, restoration and replacement of the damaged habitat or acquisition of equivalent habitat, and compensation of the public for the value of the damaged resources until full recovery. NOAA has this authority under the National Marine Sanctuary Act 16 USC 1431 et. seq.



W. Goodwin - FKNMS

Pieces of a damaged elkhorn coral were aggregated onto a concrete base and cemented to the reef during restoration of a grounding site.

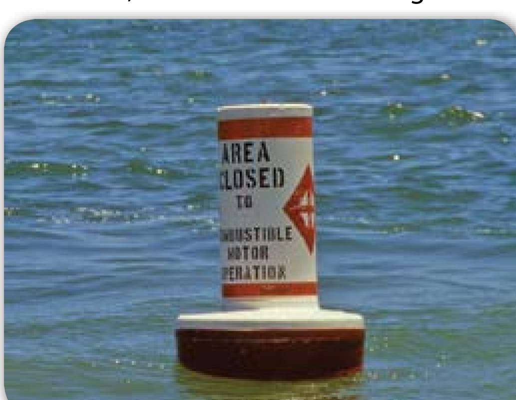
Restoration of seagrasses may be possible, but preservation is the most effective way to sustain seagrass resources

Margaret O. Hall

Seagrasses perform important ecological functions, including provision of essential habitat, production of organic matter, trophic transfers to adjacent habitats, nutrient cycling, and sediment stabilization. They are also biological sentinels of the influence of humans on coastal ecosystems. Worldwide, seagrasses have been adversely impacted by coastal development activities.

Historical development activities in south Florida that have adversely impacted large areas of seagrass resources include bridge, roadway, and causeway construction; channel dredging; harbor development; pipeline installation; and filling for development. The historical loss of seagrass habitat has resulted in an increased awareness of the need for seagrass protection, monitoring, management, and restoration.

Many development activities that historically impacted seagrass resources were permitted by state and federal regulatory agencies with the condition that at least an equal area of seagrasses be restored or created to compensate for the loss. However, even with the best intentions, the track record of seagrass restoration projects is poor. Creation of new areas of seagrass habitat is difficult because of the scarcity of sites with the necessary physical and biological parameters required for the establishment and persistence of seagrass plants. If seagrass losses have occurred due to decreased water quality, restoration or creation should not be attempted without improving water quality conditions.



FKNMS

Establishment of areas where boats with motors are excluded (no-motor zones) is an effective way to protect seagrasses and wildlife from boat traffic. No-motor zones are delineated with buoys showing an orange cross within an orange diamond.

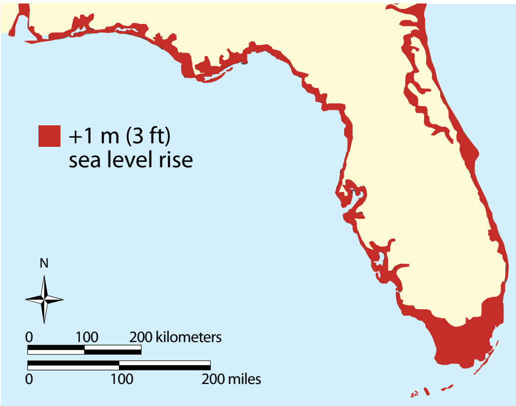
Resource managers should emphasize avoidance, minimization, and preservation of seagrass habitat during the regulatory review process of proposed development activities. Preservation is the only management option that maximizes the chance for the continued existence of remaining seagrass resources. Other options that can facilitate the continued existence of seagrass resources include reduction of point and nonpoint sources of water pollution to nearshore waters, education of boaters, legislation and enforcement, and public education. Improvement of wastewater and stormwater treatment removes sources of nutrient pollution to coastal waters and can increase the survival of seagrasses. Excluding motorboat traffic from areas can eliminate damage from propeller scarring. The lack of disturbance of motorboats also increases the habitat value of seagrass meadows to wildlife by eliminating a source of disturbance. Idle-only zones and restricting the use of deep draft vessels in shallow areas can also help protect seagrasses.

The establishment of aquatic preserves is an essential, proactive management option to protect large areas of aquatic habitats from the impacts of coastal development. Education of boaters, tourists, and residents on the importance of seagrass habitats to coastal fisheries will help generate support for future legislation for preservation of important natural resources at risk.

Sea-level rise and altered hydrology are impacting mangrove communities

Victor Engel

Mangrove forests in south Florida are subjected to two types of hydrologic disturbance due to human activities: accelerated sea-level rise as a result of climate change, and alterations to freshwater inputs from upland sources. How these disturbances affect the five types of mangrove communities present in south Florida largely depends on the rate at which freshwater inputs and sea level change, and on local factors, such as the amount of nearby development, land surface slopes, substrates, and the type and quality of inland habitats.



Adapted from Overpeck and Weiss (2009)

Projected changes to the Florida coastline with a 1 meter (3.3 feet) rise in sea level. The Florida Keys, the southern part of the Everglades, and a large portion of Miami-Dade County would be underwater.

As sea level rises, the salt-tolerant mangrove communities can be expected to shift inland in areas where there is available slope and substrate. In many areas, particularly in Everglades National Park, mangrove communities may expand into the interior freshwater marshes and hammocks. Historical aerial photography indicates that mangroves have already moved on average about 1.5 kilometer (1 mile) and as much as 3.3 km (2 mi) inland from coastal zones in southeast Florida over the past half century. This could be caused by both the reduction in freshwater discharges associated with development and drainage of the Everglades, and with the sea-level rise that has already occurred during the 20th century.

Sea-level rise is expected to cause an increase in the net loss of mangrove communities in those areas of south Florida where mangroves are currently limited to the coastal margin by adjacent development and limited to the inland margins by upslope land surfaces. Soil types and the local hydrologic setting (e.g., groundwater influences) will also play a large role in determining how these systems will respond to changes in sea level. A better understanding of the causes of sea-level rise and the role local factors will play in determining the future of mangrove communities in south Florida is required to plan for and to mitigate pending changes.

Why is sea level rising?

Sea level is expected to rise during the next century primarily due to thermal expansion of seawater as it warms with increasing air temperatures (i.e., global warming). Warm water expands more than cold water for a given amount of heating. Therefore, the amount sea level will change as a result of warming will vary according to the temperature of the regional waters. In south Florida, where waters are typically warm, thermal expansion is expected to be the major contributor to sea-level rise. Sea level is also expected to rise as a result of melting glaciers and ice sheets in polar regions and high altitudes. On shorter time scales, sea level also fluctuates in response to changes in atmospheric and oceanic circulation patterns. The magnitude of these shorter term fluctuations can be as large as or larger than those associated with climate change and global warming.

Thus, increases in sea level often appear nonlinear, with large, short-term fluctuations imposed upon longer-term trends.

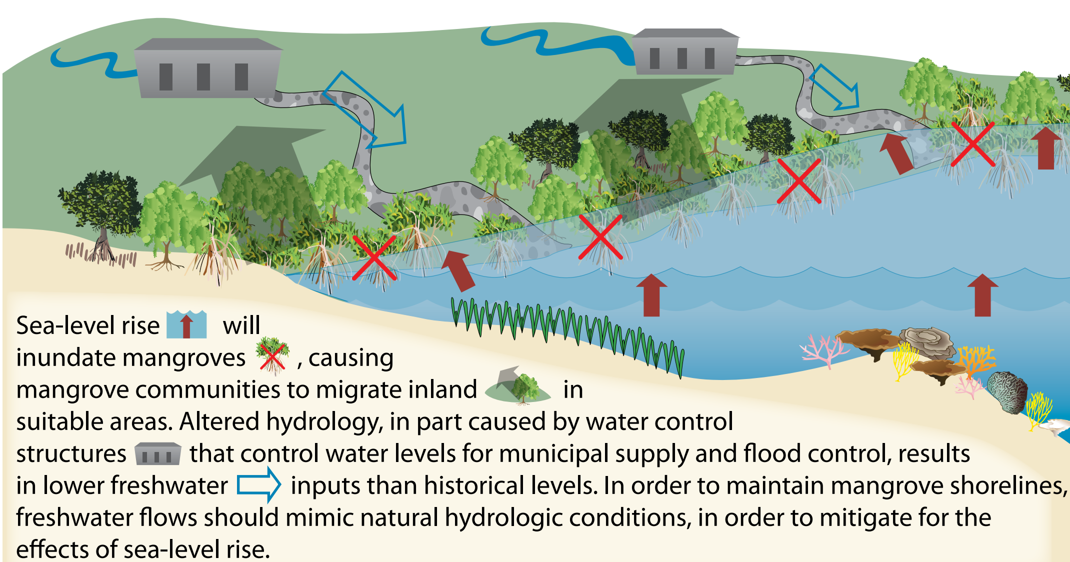
Sea level in Florida

Since the last glacial period that ended approximately 15,000 years ago, sea level has risen more than 120 meters (400 feet). The rate of sea-level rise during this period was not constant, and it slowed over the last 3000 – 5000 years to an average rate of 0.1 – 0.2 millimeters (0.01 inches) per year. Soil core analyses suggest that coastal mangrove communities in some parts of south Florida expanded their range during this time, due, in part, to high rates of peat production and sediment trapping generated by mangrove forests, which allowed these communities to "march" seaward. Although sea level was relatively stable and rose very slowly over the past several thousand years, the rate of sea-level rise in Florida over the past 100 years has increased to 2 – 3 mm (0.08 – 0.12 in) per year.

It is not known exactly how much and how fast sea level will rise over the next century. One estimate by the Intergovernmental Panel on Climate Change (IPCC) suggests that sea level will rise along the Florida coast from 20 – 56 centimeters (8 – 22 inches) by 2100. However, this estimate is highly uncertain due to a lack of information on several important factors, including ice sheet dynamics, and uncertainties regarding the global carbon cycle (e.g., fossil fuel consumption and the carbon dioxide [CO_2] fertilization effect). An alternative estimate is based on the extrapolation of the historical tide gauge data collected since 1941 in Key West, which suggests an increase in sea level in this region of 15 – 31 cm (6 – 12 in) by 2080, a rate similar to that predicted by the IPCC. Projections based on historical data are problematic if the interactions among the oceans, ice sheets, and atmosphere differ from the historical conditions during which the data were collected. These relationships are expected to change in the future with the increases in temperature caused by the buildup of CO_2 and other greenhouse gases. For these reasons, the IPCC estimates and the estimates based on data analysis of tidal records may be considered conservative.

Importance of upland freshwater resources

Freshwater inputs from upland interior areas shape many of the mangrove communities present in south Florida.



Sea-level rise will inundate mangroves, causing mangrove communities to migrate inland in suitable areas. Altered hydrology, in part caused by water control structures that control water levels for municipal supply and flood control, results in lower freshwater inputs than historical levels. In order to maintain mangrove shorelines, freshwater flows should mimic natural hydrologic conditions, in order to mitigate for the effects of sea-level rise.

The St. Lucie Canal shunts water to the Atlantic Ocean that under natural conditions would flow through the Everglades, causing major alterations in the sawgrass and mangrove communities.

Many of the organisms that inhabit estuarine mangrove communities rely on the moderating influences of seasonal freshwater inputs to complete their life cycles and to escape marine predators. Freshwater flows to coastal mangroves carry nutrients and sediments. Reduced flow during the dry season can result in moderately damaging high salinity. Freshwater sources also regulate soil chemistry and help to prevent the accumulation of toxins caused by sulfate reduction in anaerobic saline soils. In areas with little or no freshwater inputs or with limited tidal exchange, nutrients are typically low and the mangrove trees can become stunted, directing most of their growth belowground into roots. Groundwater upwelling can also play a role in determining community composition in these systems.

In areas where water levels are managed for flood control, mosquito control, or water supply, the total amount, quality, and timing of freshwater entering a mangrove community may change relative to historical values. In many areas, such as in the St. Lucie and Caloosahatchee estuaries, the current amount of freshwater discharges far exceeds historical values. These alterations can cause major disruptions in the life cycles of many estuarine organisms, as well as shunting historical freshwater flows away from the Everglades. Freshwater flows that mimic historical conditions, or are designed to minimize negative impacts on the ecosystem, will be required to help mitigate the potentially damaging effects of sea-level rise on existing mangrove communities. In many areas, such as in Everglades National Park, increasing or restoring freshwater flows to the coastal zones will be necessary to help offset the loss of inland systems caused by saltwater intrusion into surface waters and the migration of mangroves inland. As pressure from sea-level rise and the need for freshwater resources increases, it will challenge efforts to maintain natural hydrologic regimes in the remaining estuarine mangrove habitats.

Mangroves found along the shoreline of Shark River, Everglades National Park.

Water quality protection programs are an important management tool

Fred McManus and William L. Kruczynski

An important part of the Florida economy is linked to tourism, and a healthy tourism economy is in part dependent upon a healthy environment. Protecting water quality is essential for maintenance of healthy environments. There are two prime examples of interagency cooperation in addressing impacts of water quality on coastal waters and related environmental resources in south Florida.

Florida Keys National Marine Sanctuary Water Quality Protection Program

The Florida Keys National Marine Sanctuary was created in 1990 to include about 10,000 km^2 (3900 mi^2) of coastal and marine waters, extending from just south of Miami to the Dry Tortugas. The Sanctuary includes living coral reefs, seagrass meadows, and mangrove islands. These environments support high levels of biological diversity and are susceptible to damage from human activities. Congress recognized the role of water quality in maintaining Sanctuary resources and directed the United States Environmental Protection Agency and the State of Florida to develop a Water Quality Protection Program for the Sanctuary. This was the first such program ever developed for a marine sanctuary.


NPS

Protecting water quality is essential for a healthy tourism economy.

Important accomplishments of the Water Quality Protection Program

- Established and funded a comprehensive status and trends monitoring program for water quality, coral reefs, and seagrasses. This monitoring program is the preeminent coral reef ecosystem monitoring program in the world.
- Funded 25 research projects that identify cause and effect relationships between pollutants and ecological impacts. The results were instrumental in garnering support for expenditures for upgrading wastewater and stormwater infrastructure in the Florida Keys.
- Designated all Florida waters within the Florida Keys National Marine Sanctuary as a no-discharge zone for boat sewage.
- Partially funded the construction of a pilot Advanced Wastewater Treatment Plant for the Little Venice area of Marathon, Florida, and conducted water quality monitoring to document improvements in water quality as a result of upgrading inadequate on-site wastewater systems.

The purpose of the Program is to recommend corrective actions and compliance schedules that address sources of pollution in order to restore and maintain the chemical, physical, and biological integrity of the Sanctuary. This includes restoration and maintenance of a balanced, indigenous population of corals, shellfish, fish, and wildlife, and recreational activities in and on the water.

J. Luo - UM/RSMAS

Sponges and benthic algae on hardbottom communities are dependent on good water quality.

In addition to recommending corrective actions, the Program also includes a long-term comprehensive monitoring program that tracks the status and trends of the coral reefs, seagrasses, and water quality resources. It was determined that existing management actions were not adequate to prevent continuing environmental degradation. So, pollution sources, including domestic wastewater, stormwater, marinas and live-aboards, hazardous materials, mosquito spraying, and canal water quality were targeted for corrective actions. The plan to address those sources of pollution was finalized in 1996 and was included as the Water Quality Action Plan in the Sanctuary Management Plan that was implemented in 1997. The Management Plan is reviewed every 5 years.

South Florida Coral Reef Initiative

The United States Coral Reef Task Force recommended the development of a plan to address curtailment of water pollution on reefs outside the boundaries of the Sanctuary. The development of a Local Action Strategy was initiated in 2003 to address coral reef conservation and management in southeast Florida. The Local Action Strategy includes four focus areas: land-based sources of pollution; fishing, diving, and other uses; maritime industry and coastal construction; and, awareness and appreciation. The goals of the Strategy for land-based sources of pollution are for local, state, federal and other partners to: characterize the existing condition of the coral reef ecosystem; quantify, characterize, and prioritize the sources of pollution that need to be addressed based on impacts to the reefs; and, reduce impacts of land-based sources of pollution to the coral reef ecosystem. A Land-Based Sources of Pollution Focus Team was established and has developed detailed action strategies and projects to meet the goals. One important ongoing action strategy is to assimilate existing data to quantify and characterize the sources of pollution and identify the relative contributions of the different sources.

R. Molina

Stormwater runoff and wastewater increase turbidity and the concentration of nutrients and other pollutants, which are harmful to marine resources.

Management actions are being implemented to improve water quality in the Florida Keys

Gus Rios, William L. Kruczynski, Geofrey Mansfield, and Timothy Banks

Historically, development in the Florida Keys relied on the use of cesspools and septic tanks for wastewater disposal. Those systems provide little or no treatment in areas with rock substrates and high groundwater tables. Over the past 20 years, aerobic treatment units and traditional "secondary" wastewater treatment plants have also been used. Although the aerobic treatment units and secondary plants provide better treatment than septic tanks and cesspools, they are not efficient at removing nutrients (i.e., phosphorus and nitrogen). Excessive nutrients from inadequately treated wastewater are a primary contributor to water quality degradation in nearshore waters.

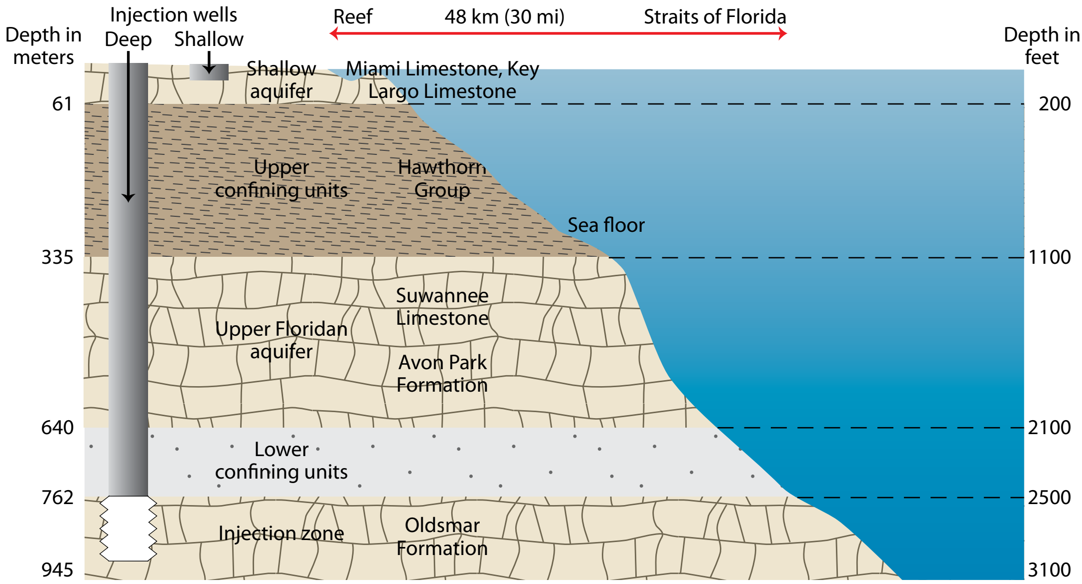
In 1991, Monroe County adopted its Comprehensive Plan pursuant to Rule 28-20 of the Florida Administrative Code, the land planning regulations for the Florida Keys Area of Critical State Concern. Adoption of the Plan was challenged in an administrative hearing. In the 1995 Final Order on the case, the hearing officer found that sewage and stormwater discharges were degrading the nearshore waters of the Keys and that these waters exceeded their "carrying capacity" for additional nutrient pollutant loads. In order to address this issue, the Florida Administration Commission, through rules that became effective in 1997, promoted a comprehensive "Work Program" with a schedule for corrective actions, such as the identification and elimination of cesspools and development of a comprehensive sanitary wastewater master plan. One specific goal of the Work Program and amended Comprehensive Plan was to build wastewater facilities to meet advanced wastewater treatment or best available technology standards to reduce nutrient loading to nearshore waters.

The 1999, the Florida Legislature bolstered the Comprehensive Plan and the Administration Commission rules by establishing binding treatment and disposal requirements for all sewage treatment and disposal facilities in Monroe County, including sewage treatment plants regulated by the Florida Department of Environmental Protection and on-site sewage treatment and disposal systems (OSTDS) regulated by the Florida Department of Health. Section 6 of Ch. 99-395, Laws of Florida, became effective in June 1999 and required all sewage disposal systems in Monroe County to comply with new stringent effluent standards by July 1, 2010.

Chapter 99-395 prohibited new surface water discharges of wastewater and required elimination of existing surface water discharges by July 1, 2006. Under this law, wastewater treatment plants with design capacities under 3.8 million liters (1 million gallons) per day could discharge treated effluent to Class V injection wells, drilled to 27 meters (90 feet) and cased to 18 m (60 ft). Wastewater facilities with a design capacity equal to, or greater than, 3.8 million L (1 million gal) per day were required to discharge treated effluent

	Biological Oxygen Demand (mg/L)	Total Suspended Solids (mg/L)	Total Nitrogen (mg/L)	Total Phosphorus (mg/L)
Best Available Technology facilities, <100,00 gallons per day, includes Onsite Sewage Treatment and Disposal Systems and package plants	10	10	10	1
Advanced Wastewater Treatment facilities, >100,000 gallons per day	5	5	3	1

Wastewater treatment requirements for Monroe County, Florida.



Adapted from City of Key West Sewage Treatment Plan: Operations Management International, Inc. www.keywestwastewater.com

A comparison between the depth of a shallow and deep injection well. Deep injection is required for all treatment plants in Monroe County with a capacity equal to, or greater than, 3.8 million liters (1 million gallons) per day.

into deep injection wells with a minimum depth of 610 m (2000 ft). In addition, this law promotes reuse of treated wastewater.

Section 4 of Chapter 99-395, Laws of Florida, gave local governments within the Florida Keys Area of Critical State Concern the authority to enact ordinances to require connection to the central wastewater collection and treatment systems. This is a critical mechanism to promote compliance that is tied to the Area of Critical State Concern designation.

Recently, the Florida Legislature extended the July 1, 2010 wastewater compliance deadline until December 31, 2015 and incorporated all the treatment and disposal requirements, formerly in Section 6 of Chapter 99-395, Laws of Florida, into Section 403.086(10) of the Florida Statutes. However, this new section of the Florida Statutes makes it clear that, in addition to the responsibilities of individual property owners, local governments and special wastewater districts in the Keys are responsible for building and operating appropriate wastewater facilities within their jurisdictions, connecting package plants and OSTDS, and helping ensure that homeowners remaining on OSTDS and package plants located outside of the centralized sewer areas comply with the applicable requirements. Some local governments in the Keys, including the City of Key West and Layton, have either already met the wastewater requirements, or, like Marathon and the Key Largo Wastewater Treatment District, have made good progress toward meeting the requirements. While progress has been made in upgrading and building new wastewater infrastructure in the Florida Keys, there is still a tremendous amount of work that remains to be done. The Florida Department of Environmental Protection and the Florida Department of Health will continue to work with the local governments and owners of package plants and OSTDS in Monroe County to promote timely completion of the required facilities and to allow connection to the new centralized wastewater systems. In addition, the Water Quality Protection Program Steering Committee, and all the state and federal agencies with jurisdiction, will continue to work with the local governments in Monroe County to identify and generate the necessary financial resources to implement the County Wastewater Master Plan and to achieve compliance with the December 31, 2015 deadline.

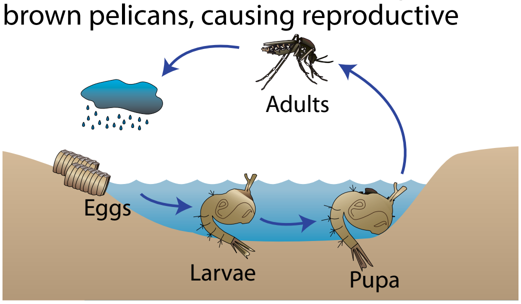
Integrated mosquito management strategies are required to control mosquito populations in the Florida Keys

Richard H. Pierce

The subtropical environment of south Florida supports more than 40 species of mosquitoes. A common mosquito is the black salt marsh mosquito (*Ochlerotatus* [*Aedes*] *taeniorhynchus*). Mosquito-borne diseases of concern today are Dengue fever, Eastern Equine, St. Louis, and West Nile encephalitis, as well as dog heartworm. With an economic dependence on tourism and outdoor activities, controlling mosquitoes is essential to human health and the economy of south Florida and the Keys.

The first attempt at mosquito control in the Florida Keys was unsuccessful. In 1929, settlers built a bat tower on Sugarloaf Key to attract bats to eat adult mosquitoes. However, no bats have colonized the tower, which still stands today.

In 1949, the Monroe County Anti-Mosquito District was created by a special act of the Florida Legislature. Potent chemicals (e.g., DDT, Malathion) were applied and were very effective. However, they caused long-term environmental problems, and bioaccumulated in the food chains of American bald eagles and brown pelicans, causing reproductive failure. The District progressed to use less persistent pesticides, which reduced the long-term impacts. The use of chemical pesticides continues to pose a risk to public health and nontarget organisms, such as beneficial insects and aquatic organisms.



The black salt marsh mosquito occurs from south Texas to New Hampshire. The vast majority of mosquito complaints in the Keys are due to this species. Adults lay up to 100 eggs close to the high water mark. These eggs can survive for a long time until rain or high waters stimulate them to hatch. After hatching, they spend 7 days as larvae, 1 – 2 days as pupae, and 17 days as adults (four stages total). They are a "brooded" mosquito, which means when a tidal or rainfall event covers the eggs with water, they all hatch at about the same time. They are strong fliers and migrate in large numbers 8 – 64 kilometers (5 – 40 miles) from the hatch site.

The adulticides currently used by the Florida Keys Mosquito Control District are Naled and Permethrin. Naled is an organophosphate insecticide, registered since 1959 for use in mosquito control and growth of food crops and ornamental plants. It is a fast-acting, nonpersistent insecticide that rapidly breaks down in water. However, both Naled and its byproduct, dichlorvos, are classified as very highly toxic to aquatic invertebrates, so even short-term exposure to nontarget organisms is a concern.

Permethrin is a broad spectrum synthetic insecticide, registered since 1977 for use in home, lawn, agricultural, industrial, and mosquito control applications. Permethrin is highly toxic to insects and aquatic invertebrates and exhibits a high bioconcentration factor in aquatic organisms. The amounts of Naled and Permethrin applied for mosquito control operations are well below lethal doses for mammals; however, sublethal effects include neurological, reproductive, genetic, and immune function impacts. In addition, their high toxicity to aquatic organisms raises concerns for applications that drift into water environments. Therefore, the use of chemical controls for mosquitoes must be carefully weighed against their impacts.

Today, the Florida Keys Mosquito Control District uses integrated mosquito management strategies, a science-based approach that includes biological control (mosquito fish) and a larvicide (*Bacillus thuringiensis* var. *israelensis*) that has reduced the amount of toxic adulticides needed by 65% over previous levels.

Present restoration efforts depend upon an accurate historical record

G. Lynn Wingard

Natural systems change at many spatial scales, from microscopic to system-wide landscape changes, and over many time scales, from instantaneous to hundreds or thousands of years. To understand how ecosystems function, they must be examined over broad scales of time and space. This is especially important when society decides to restore an altered landscape, as is presently being done in south Florida. Many questions are raised: "To what condition is the ecosystem being restored? What are the goals? What are the targets for restoration? What are the effects of restoration going to be on the environment of the future?" Landscape managers rely on scientists to provide them with answers to these questions as a framework for restoration planning.

For the estuaries, one of the primary goals of restoration is to restore natural salinity patterns. Salinity in estuaries is determined by many factors. In south Florida, the primary natural drivers of salinity are seasonal rainfall and runoff from wetlands. Human alterations of the environment through the construction of water-control structures have profoundly altered the flow of freshwater into the estuaries during both the wet and dry seasons of the year.

Some key scientific questions that landscape managers need to understand in order to set restoration targets are:

- What were the spatial and temporal salinity patterns in south Florida estuaries prior to significant alteration of the environment?
- How did these salinity patterns relate to rainfall, climate, freshwater influx, and sea level?
- How did 20th century anthropogenic changes offset the natural patterns of change?

R. Molina

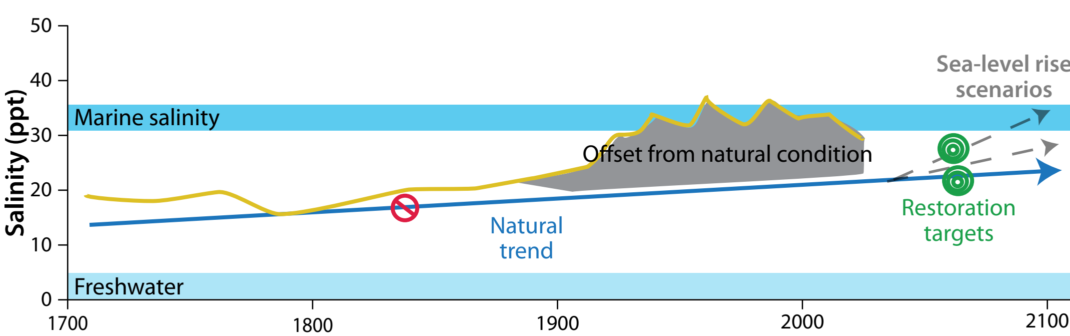
The flow of water across the south Florida landscape has been modified into a series of canals with structures that control the amount of water delivered to estuaries and coastal areas (St. Lucie Lock in the Okeechobee waterway, Martin County).

FDOT

FDOT

The images above show the dramatic change in land-use patterns in western Miami-Dade County. Managers are setting realistic restoration goals and targets that include the built environment, resource needs, and predictions of the future, such as sea-level rise and climate change.

Since restoration of the south Florida ecosystem is expected to be a 50-year project, setting goals and targets is further complicated by predictions of rapid sea-level rise and climate change in the future. By looking at long-term patterns of change, scientists can understand how global factors have affected the estuaries of south Florida in the past, and use this information to make predictions about how these factors will impact the future. This long-term view of change allows restoration managers to set goals and targets for restoration that can be realistically obtained, and that will be sustainable in the long term.



This hypothetical model illustrates the importance of understanding natural environmental trends when setting targets for restoration. The golden line represents hypothetical salinity patterns over the past 300 years. The blue line represents the natural trend of increasing salinity over the same time period. An assumption is made that at least some of the offset seen between 1900 – 2000 (shaded gray area) is due to human alteration of the environment. Restoration targets set to replicate salinity during the 1800s (red circle) would not be attainable or sustainable. Restoration to pre-1900 conditions would be an attempt to overcome the natural, as well as the human-induced changes to the environment. Instead, restoration aims to return to the natural trend (green target on blue line)—a prediction of where the system would have been if humans had not interfered. Taking projected sea-level rise scenarios into account, restoration may need to aim for a target adjusted to allow for increasing salinity (green target on gray dashed line).

Completion of the Comprehensive Everglades Restoration Plan will restore water flows to more historical conditions

Robert Johnson

Pre-drainage hydrology

Prior to the 1880s, water flowed freely from the Kissimmee Chain of Lakes southward down the meandering Kissimmee River and into Lake Okeechobee. Water then flowed slowly out of Lake Okeechobee into the Everglades in most years. The dense sawgrass plains and custard apple swamps found in the northern Everglades and the gentle southward land slope combined to hold water levels in Lake Okeechobee at approximately 6.4 meters (21 feet) above sea level (more than 1.2 m [4 ft] higher than current wet season managed levels). At this time there were no rivers connecting Lake Okeechobee to the Atlantic coast or the Gulf of Mexico, but a narrow marsh connection passed limited flows into the headwaters of the Caloosahatchee.

Since virtually all the outflow from Lake Okeechobee was to the south, high water levels in the lake served as a major driver of water flow through the Everglades and into downstream coastal areas. During pre-drainage times, the Everglades were extremely wet and water flowed slowly southward for all but the driest years. The persistence of water flow through the deeper sloughs supported nearly continuous outflows to the coastal rivers and embayments. This slow water flow resulted in a temporal buffering of the natural patterns of seasonal rainfall, extending freshwater flows well into the dry season, and sometimes flows were continuous for more than a year. This eased impacts of drought and facilitated stable salinity conditions in the downstream tidal rivers and nearshore estuaries.

Post-drainage hydrology

Drainage and development in south Florida occurred in three major phases. Drainage began in the early 1880s with the construction of canals to connect the Kissimmee Chain of Lakes, deepening and straightening the Kissimmee River, and constructing a humanmade outlet from Lake Okeechobee to the Caloosahatchee. The focus of these drainage projects was to improve drainage in the Kissimmee Valley and lower water levels in Lake Okeechobee to eliminate the direct connection with the Everglades, thereby draining the northern Everglades for agricultural use. The outcome of this first phase of drainage was a drop in Lake Okeechobee water levels by 0.3 – 0.6 meters (1 – 2 feet), which began a long sequence of flow reductions to the Everglades.

The second phase of drainage focused on constructing canals across the northern and central Everglades to connect Lake Okeechobee directly to the Atlantic Ocean, constructing an outlet from the lake to the Saint Lucie River, and constructing levees around the southern shoreline of the lake. These changes further lowered water levels in the lake, severed the natural flow connection with the Everglades, and expanded the agricultural area south of the lake. Between 1905 – 1930, four large canals (i.e., West Palm Beach, Hillsboro, North New River, and Miami Canals) were constructed across the Everglades. These canals intercepted natural sheetflow and drained the water to tide. These coastal outflows remained uncontrolled until the late 1940s. Reduced flows and drainage to tide had the greatest impact on flows through the Everglades and the downstream estuaries. The cumulative effect of all of the changes allowed development in the northern portion of the area and dried out the majority of Everglades for lack of water.

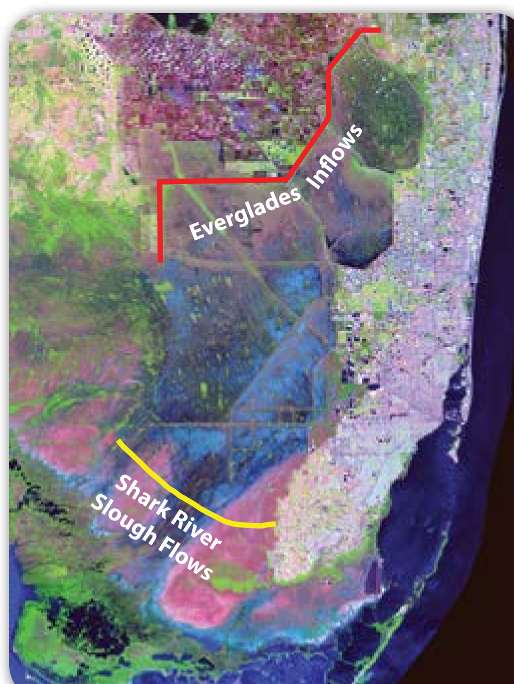
The third phase of drainage and development coincided with the authorization of the Central and Southern Florida Project, a joint federal-state comprehensive water resources program that was initiated in 1948. This phase included the construction of an Eastern Protective Levee System, stretching from Lake Okeechobee into southern Miami-Dade County, and a series of water storage impoundments (Water Conservation Areas) that created five hydrologically isolated compartments in the central Everglades wetlands. While the construction of the Water Conservation Areas improved the conditions in much of the central Everglades relative to prior periods of uncontrolled drainage, the levees used to create the impoundments blocked the natural sheetflow to the southern portion of the Everglades and downstream estuaries. The result was a more pulsed flow, in which water was held back from the southern Everglades during periods of low rainfall and released in massive volumes during high rainfall periods. This management approach caused wide fluctuations in salinities and nutrient loadings to the downstream tidal rivers and nearshore waters and led to shifting patterns in submerged aquatic vegetation and periodic algal blooms.

Comprehensive Everglades restoration

Large-scale restoration of water flows in south Florida began in the early 1990s in the northern portion of the watershed with the Kissimmee River Project, and in the southern Everglades with the Modified Water Deliveries and C-111 South Dade Projects. Both initiatives have a goal of returning surface water flows to their historical flow paths. The Comprehensive Everglades Restoration Plan (CERP) was authorized in 2000 and provides a framework for the protection and restoration of the water resources of central and southern Florida, including the Everglades. The goal of CERP is to capture and store excess freshwater flowing to tide and redirect it to areas that need it the most, with the majority allocated to the protection of the environment.

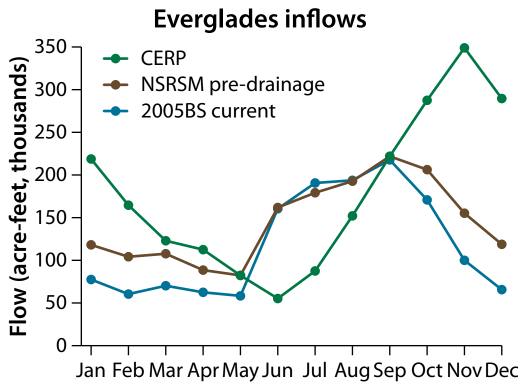
Construction of CERP projects are being implemented in phases and the proposed third generation of CERP components is currently being evaluated through a new streamlined planning process known as the Central Everglades Study Plan. This suite of projects focuses on increasing the volume of clean water passing southward through a more connected system of Water Conservation Areas and is an attempt to restore the historical connection between Lake Okeechobee and Everglades National Park.

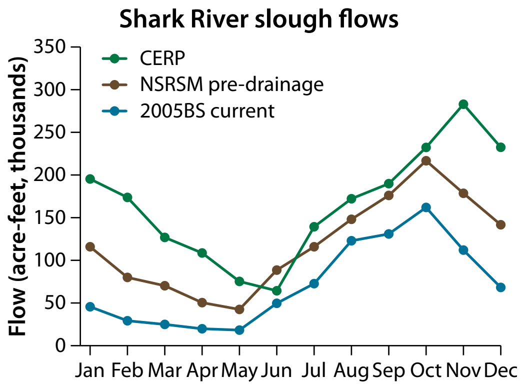
A series of hydrologic simulation models have been used to compare an estimation of pre-drainage flows through the Everglades with flows under the current water management conditions and flows that would result from completion of CERP.



This map depicts two transects where water flow was modeled. The northern one (red) represents the boundary of Everglades Inflows into Water Conservation Areas (remnant Everglades) and the southern one (yellow) represents flows into the Shark River Slough and coastal areas, including Florida Bay.

These two graphs show the predicted changes in annual average flow volume (acre-feet per year) and monthly flow distributions based upon three hydrologic simulation models of Everglades water flow for a 36- to 41-year period. Both graphs depict a comparison of simulations of flow conditions of the restoration targeted pre-drainage condition (brown line) with flow conditions under the current water management condition (blue line) and flow conditions following implemention of the Comprehensive Everglades Restoration Plan (green line).





The plot on the left shows the simulated inflows into the remnant Everglades along the northern boundary of the Water Conservation Areas (Everglades inflows). During pre-drainage times, inflow to the Everglades averaged 2.1 million ac-ft/yr (brown). Flows decreased during the dry season to a minimum flow in June and increase during the wet season to a maximum flow in October – November. Under current water management practices (blue), the annual average flow is 1.4 million ac-ft/yr, which is approximately 67% of the pre-drainage target flows. The main differences between pre-drainage flows and current flows at this location are flows currently diverted from Lake Okeechobee into the northern estuaries via the St. Lucie Canal and the Caloosahatchee. The original CERP simulation (green) shows that completion of the Plan would increase inflows to the Everglades to an average of approximately 1.7 million ac-ft per year, approximately 80% of the pre-drainage target flow. However, as a result of drainage from the Everglades Agricultural Area, simulated flow under CERP results in delivery of much more water to the Everglades during the early wet season (June – August) compared to pre-drainage condtions. Increased water storage is required to retain this water and shift the deliveries toward the early dry season. The Central Everglades Study will attempt to capture and store this wet season runoff, as well as the majority of remaining regulatory releases currently being discharged to the Caloosahatchee and St. Lucie estuaries. Redirecting this water southward would more closely approach pre-drainage target flows and enhance dry season water deliveries to the Everglades and downstream estuaries.

The plot on the right shows simulated flows through the southern Everglades at the center of Shark River Slough. Pre-drainage flows (brown) at this point averaged 2.0 million ac-ft/yr and flows under the current water management regime (blue) average 0.86 million ac-ft/yr, representing 43% of targeted flow. The original CERP simulation (green) shows that completion of the Plan would increase flows into the southern coastal areas to approximately 1.4 million ac-ft/yr, 70% of the pre-drainage flow target. At this location, the seasonal pattern of flows for both the current (blue) and CERP (green) simulations are similar to pre-drainage simulation. However, substantially greater flows are needed throughout the year to more closely match the restoration target. The new Central Everglades Study will attempt to capture and store the wet season runoff in the northern portion of the watershed and redirect this water southward to greatly enhance water deliveries to the southern Everglades and downstream estuaries.

South Florida Ecosystem Restoration is more than the Comprehensive Everglades Restoration Plan

Peter B. Ortner

The quality of the south Florida environment today is the result of efforts over the past 100 years to drain and develop the land. Throughout the 20th century, a vast network of drainage canals were installed and maintained to improve flood control and water supply for the burgeoning human population. It is now recognized that those efforts had unintended consequences, including degradation of water quality of fresh and nearshore waters, massive loss of wildlife habitat and subsequent population declines of many species of wildlife, reduced biodiversity, saltwater intrusion into the drinking water aquifer, and problems with invasive plants and animals. Pollution of Lake Okeechobee, drying of the Everglades, and seagrass die-off and subsequent algal blooms in Florida Bay focused a recognition of the severity of the consequences of unbridled development and poor ecosystem management. The future of the south Florida ecosystem depends upon the will of citizens and their elected officials to plan and implement successful restoration actions.

Restoration planning efforts have been initiated, but the blame for environmental stresses and disputes over the roles and responsibilities of the levels of government have been pernicious. In 1988, the federal government sued Florida for allowing pollution of federal lands. In 1989, Congress passed the Everglades Expansion Act with the goal of improving water quality and quantity delivered to the Everglades. State, federal, and tribal parties bickered over what was required for restoration, and signed a consent decree in 1992 accepting judicial oversight of Everglades restoration. In 1993, President William J. Clinton signed an Executive Order that required federal agencies to organize an interagency task force and work with local partners. In 1994, Florida passed the Everglades Forever Act that provided funding for improving water quality delivered to the Everglades by establishing stormwater treatment areas, implementing best management practices, and establishing environmentally-acceptable nutrient criteria.

NPS

South Florida plants and animals are adapted to alternating wet and dry seasons. Changes to historical flow regimes have disrupted the feeding and nesting cycles of many species of wildlife.

The Water Resources Development Act (WRDA) of 1996 established the South Florida Ecosystem Restoration Task Force. The 14-member task force consists of federal, state, tribal, and local government representatives. The goals of the Task Force are to:

- Coordinate the development of consistent policies, strategies, plans, programs, projects, activities, and priorities addressing the restoration, preservation, and protection of the entire south Florida ecosystem, including the south Florida peninsula, the Florida Keys, and the Dry Tortugas.
- Exchange information regarding programs, projects, and activities of the agencies and entities represented on the Task Force to promote ecosystem restoration and maintenance.
- Facilitate the resolution of interagency and intergovernmental

conflicts associated with restoration of the south Florida ecosystem among the agencies and entities represented on the Task Force.
- Coordinate scientific and other research associated with restoration of the south Florida ecosystem.
- Provide assistance and support to agencies and entities represented on the Task Force in their restoration activities.

WRDA (1996) also authorized the Restudy that includes the proposed re-engineering of the water management network managed by the South Florida Water Management District. Based on the Restudy, the Comprehensive Everglades Restoration Plan was authorized in the Water Resources Development Act of 2000. Concurrently, Florida passed the Everglades Forever Act, which provides the ability to acquire the land necessary to implement the Plan.

The overall goal of South Florida Ecosystem Restoration is to restore, preserve, and protect the entire south Florida ecosystem while providing for other water-related needs of the region, including water supply and flood protection. Successful restoration requires:

1. Restoring the quality, quantity, timing, and distribution of freshwater. The Comprehensive Everglades Restoration Plan provides the details for quantity, timing, and distribution of freshwater necessary for the Everglades geographic area. It is the responsibility of the state to ensure that the water quality meets acceptable standards for maintenance and restoration of aquatic resources.
2. Restoring and enhancing the natural ecosystem, including habitat protection and biodiversity.
3. Fostering the compatibility of the developed and natural environments by controlling urban sprawl and encouraging redevelopment.

It is estimated that the total cost of South Florida Ecosystem Restoration is $16 billion, approximately half of which is required to implement the Comprehensive Everglades Restoration Plan. Funding responsibility is a 50:50 split between federal and state governments. To date, most of the progress in implementing South Florida Ecosystem Restoration has been associated with water delivery to the Everglades, and funding has been secured to begin 68 individual projects in the Comprehensive Everglades Restoration Plan. Unfortunately, the availability of funds has often been out of phase with project implementation schedules. Little progress to date has been made toward other South Florida Ecosystem Restoration goals. One exception has been the acquisition of critical areas of land through purchase using Florida Forever Act funds, or protection through establishment of conservation easements.

The consensus among scientists on the Working Group, a committee organized to assist the Task Force in planning, is that implementation of the Comprehensive Everglades Restoration Plan alone will not result in the restoration, preservation, and protection of the entire south Florida ecosystem. The future of the south Florida ecosystem depends upon the will of federal, state, and local governments to actively support and fund restoration activities that meet all of the goals of South Florida Ecosystem Restoration, a commitment made significantly more challenging in difficult economic times.


SFWMD

Controlling urban sprawl into farmlands, wetlands, and areas with a high water table is one of the many challenges of South Florida Ecosystem Restoration.

Making the connections

William L. Kruczynski and John H. Hunt

The diversity of community types and the biodiversity of life forms that inhabit them make south Florida an ecological treasure trove. Life in south Florida coastal waters is a mix of temperate and tropical organisms that includes the Florida Keys Reef Tract, the only living barrier coral reef in North America and the third largest coral barrier reef on the planet, after the Great Barrier Reef in Australia and the Mesoamerican Barrier Reef System in Central America. Numerous patch reefs and hardbottom communities occur throughout the area and provide important habitat and feeding areas for many fish and invertebrates.

NOAA

The Florida Keys Reef Tract is the third largest barrier reef on Earth and is a popular tourist attraction that fuels the local economy.

The mangrove forests in the Ten Thousand Islands, the southern tip of Florida, and throughout Florida Bay and elsewhere are fertile and productive nursery grounds for many species of marine life. They are also important nesting, roosting, and feeding habitat for many species of resident and migratory birds. South Florida contains the largest documented seagrass meadow in the world that occupies an important position between freshwater environments of the mainland and the open ocean.

The natural resources of the south Florida coastal ecosystem are used for food, fun, and fortune. Tourism, fishing, and seafood industries are major drivers of the local economy and are dependent upon healthy south Florida marine habitats. Residents and tourists alike enjoy swimming, boating, fishing, diving, snorkeling, and nature watching in the region. People who have never visited this region may connect to the unique natural resources of south Florida by taking solace that they simply exist in nature.

Many organisms require specific habitats to successfully complete their life cycles. Others, including many fish and invertebrate species with commercial and recreational importance, such as Caribbean spiny lobster, pink shrimp, groupers, and snappers, use several different habitats during their development. Many are spawned in the open ocean and travel to mangroves, seagrasses, and shallow hardbottom for shelter and sustenance during early life stages. Thus, consideration of habitat connectivity is an important component in the establishment of effective resource management.

The ecological health of the south Florida marine environment is dependent upon many factors, including good water quality. South Florida is bathed by major ocean currents from the Gulf of Mexico and wider Caribbean Sea that deliver clear and warm water that is essential to the growth and survival of local plant and animal life. Many larval forms are delivered from remote areas to south Florida via ocean currents and replenish the standing stock of marine life. Coastal waters are also connected to the open ocean by periodic upwelling of nutrient-rich waters that helps fuel primary productivity.

Human pollutants can enter the coastal ecosystem from nearfield and farfield sources. Reduction or elimination of pollutants at their sources is required to protect downstream systems. A nationwide assessment found that 64% of estuaries in the United States have moderate to high levels of eutrophication due to nutrient pollution. Improved wastewater collection and treatment systems and the elimination or treatment of point and nonpoint sources of wastewater and stormwater are required to restore and maintain ecosystem health. Proper disposal of pharmaceuticals and personal care products will help maintain healthy fish and wildlife populations.

NASA

Pollutants from nearfield and farfield sources can affect south Florida coastal waters. Excess nutrients and pollutants from the Mississippi River can become entrained in the Loop Current in the Gulf of Mexico and delivered to south Florida. Control of pollutants requires cooperation across regional and political boundaries.

Because the coastal habitats found in south Florida are physically, biologically, and economically connected, successful resource management must include an appreciation of the interaction of all components of the coastal ecosystem. Successful management requires addressing local, regional, and global sources of pollution and communication and cooperation across political and regional boundaries. For example, the goal of the Comprehensive Everglades Restoration Plan is to capture freshwater that now flows unused to the ocean and the Gulf and redirect it to areas that need it most. In order to protect downstream areas, care must be taken to restore or maintain the quantity, timing, and distribution of salinity and other water quality parameters.

USGS

Waters surrounding Loggerhead Key, Dry Tortugas National Park. Management actions should be cognizant that the south Florida marine ecosystem is the receiving water for all upstream activities.

Effective management of natural resources requires understanding, communication, and cooperation among managers, scientists, resource users, and residents. Managers must strive to base decisions on sound, defensible scientific findings and learn to effectively communicate their information needs to scientists. Their full support of applied research and ecosystem monitoring is essential to their success. Scientists should focus on providing defensible information and communicate that information in ways that managers and the public can understand. Resource users should strive to improve their understanding of south Florida marine habitats and support their management by following applicable rules and regulations and fostering a conservation ethic. Everyone working together as a connected community, guided by knowledge of the structure and function of our south Florida marine ecosystem, will provide the best possible future for our marine environment and our quality of life.

Introduction citations

1. Bancroft, GT. 1995. Case Study: United States of America. American Association for the Advancement of Science. Workshop on Human Population, Biodiversity and Protected Areas: Science and Policy Issues, April 20, 1995. Available from: http://www.aaas.org/international/ehn/biod/banc.htm (Cited 28 Feb 2011). *A case study of Everglades National Park linking increases in human population with major changes to the natural landscape.*
2. Adeel Z, Miyazaki N. 2005. Overview of the global marine and coastal challenges. In: Miyazaki N, Adeel Z, Ohawada K (eds.). Mankind and the Oceans. Tokyo: United Nations Press. p. 1-6. *A large number of human activities are directly or indirectly dependent on a healthy marine environment.*
3. Davis JE. 2005. Alligators and Plume Birds: The Despoliation of Florida's Living Aesthetic. In: Davis JE, Arsenault R (eds.) Paradise Lost? The Environmental History of Florida. Gainesville, FL: University of Florida Press. p. 235-259. *Plume feather trade industry decimated the wading bird population of south Florida.*
4. United States Department of Interior, National Park Service. Theodore Roosevelt and Conservation. Available from: http://www.nps.gov/thro/historyculture/theodore-roosevelt-and-conservation.htm (Cited 1 Mar 2011). *A tribute to the legacy of Theodore Roosevelt in land conservation.*
5. National Oceanic and Atmospheric Administration, National Marine Sanctuaries. Management Areas Help Sanctuary Balance Diverse Uses in the Florida Keys. Available from: http://sanctuaries.noaa.gov/news/features/0110_zone.html (Updated 27 Apr 2011; cited 1 Mar 2011). *Engaging user groups is a critical element in marine spatial planning.*
6. National Oceanic and Atmospheric Administration, Florida Keys National Marine Sanctuary. The Zoning Action Plan. Available from: http://floridakeys.noaa.gov/regs/zoning.html (Cited 1 Mar 2011). *Florida Keys National Marine Sanctuary Marine Zoning Plan is a management tool designed to protect sensitive marine resources from overuse and to separate conflicting visitor uses.*
7. National Oceanic and Atmospheric Administration, Florida Keys National Marine Sanctuary. Section 1. Protecting the Living Coral Reef. Available from: http://floridakeys.noaa.gov/regs/exsum/sect1.html (Cited 1 Mar 2011). *A summary of public concerns and input of user groups that were incorporated into the development of the management plan for the Florida Keys National Marine Sanctuary.*
8. United States Environmental Protection Agency, Florida Keys National Marine Sanctuary Water Quality Protection Program. Available from: http://ocean.floridamarine.org/fknms_wqpp/pages/wqpp.html (Cited 1 Mar 2011). *A summary of the goals and objectives of the Water Quality Protection Plan for the Florida Keys National Marine Sanctuary.*
9. Southeast Florida Coral Reef Initiative. 2011. What is SEFCRI? Available from: http://www.southeastfloridareefs.net/about-us/what-is-sefcri/ (Cited 1 Mar 2011). *The goals of the Southeast Florida Coral Reef Initiative are to characterize the condition of coral reefs, quantify sources of pollution, and reduce land-based sources.*
10. NOAA. The Florida Area Coastal Environment (FACE) Program. Available from http://www.aoml.noaa.gov/themes/CoastalRegional/projects/FACE/faceweb.htm (Cited 29 Jul 2011). *The Florida Area Coastal Environment Program is a data gathering effort designed to quantify sources of nutrients and other pollutants to ocean waters of southeast Florida.*
11. Diersing N. 2006. Water Quality Answers for the Florida Keys. Sounding Line Newsletter, Florida Keys National Marine Sanctuary, Winter 2006-Spring 2007. Available from: http://floridakeys.noaa.gov/wqpp/waterfaq.pdf (Updated 1 Jan 2008; cited 1 Mar 2011). *Answers to questions concerning water quality in the Florida Keys.*
12. State of Florida, Chapter 99-395 Laws of Florida (House Bill 1993). Available from: http://www.dep.state.fl.us/south/Keys/Ch_99-395.pdf (Cited 1 Mar 2011). *State Law 99-395 requires that all sewage treatment facilities in the Florida Keys meet improved treatment standards.*
13. State of Florida, Chapter 2010-205 Laws of Florida (Committee Substitute for Senate Bill 550). Available from: http://laws.flrules.org/files/Ch_2010-205.pdf (Cited 1 Mar 2011). *Extension of deadline to meet improved wastewater treatment standards in Monroe County to December 31, 2015.*
14. Marine Protected Areas Federal Advisory Committee. 2008. Toward a National System of Marine Protected Areas. Recommendations from 2006-2007. Washington, DC: National Oceanic and Atmospheric Administration and United States Department of Interior. 66 p. Available from: http://www.mpa.gov/pdf/fac/fac_recmd_06_07.pdf (Cited 1 Mar 2011). *A guidance document on the importance and the establishment of marine protected areas.*
15. Clinton WJ, President of the United States. 2000. Executive Order 13158, May 26, 2000. Marine Protected Areas. Federal Register 65 (105), May 31, 2000/Presidential Documents, p. 34909-34911. Available from: http://www.mpa.gov/pdf/eo/execordermpa.pdf (Cited 1 Mar 2011). *Presidential Executive Order 13158 (President William J. Clinton) expanding and strengthening a comprehensive system of marine protected areas to enhance the sustainable use of the marine environment for future generations.*
16. Halpern BS, Lester SE, Kellner JB. 2009. Spillover from marine reserves and the replenishment of fished stocks. Environ Conserv. 36:268-276. *No-take marine reserves can simultaneously meet conservation objectives and benefit local fisheries adjacent to their boundaries.*
17. Cox C, Hunt JH. 2005. Change in size and abundance of Caribbean spiny lobsters *Panularis argus* in a marine reserve in the Florida Keys National Marine Sanctuary, USA. Mar Ecol Prog Ser. 294:227-239. *Lobsters within the reserve are larger than in control areas outside the reserve.*
18. Ault JS, Smith SG, Bohnsack JA, Luo J, Harper DE, McClellan DB. (2006). Building sustainable fisheries in Florida's coral reef ecosystem: positive signs in the Dry Tortugas. Bull Mar Sci. 78:633-654. *No-take marine reserves, in conjunction with traditional management, can help build sustainable fisheries while protecting the Florida Keys coral-reef ecosystem.*
19. Bohnsack J. 2002. Fishery Benefits of Marine Reserves: A Test in a Florida Recreational Fishery. FATHOM. Available from: http://www.fathom.com/feature/122653/index.html (Cited 1 Mar 2011). *Examination of world records for three game fishes show that no-take marine reserves can be a win-win situation.*
20. Cowie-Haskill BD, Delaney JM. 2003. Integrating science into the design of the Tortugas Ecological Reserve. Mar Technol Soc J. 37:68-81. *The collaboration among scientists, managers, and the various stakeholders was a critical facet in the establishment of the reserve's design.*

Further reading

Arrieta JM, Arnaud-Haond S, Duarte CM. 2010. What lies underneath: Conserving the ocean's genetic resources. Proc Nat Acad Sci. 107(43):18318-18324. *Protecting marine genetic resources is essential to ensure their sustainable use and to support the flow of future findings of medical and biotechnological interest.*

Barley G. 1993. The Florida Keys example from an activist citizen's point of view. Oceanus 36(3):15-18. *Following Congress's 1990 designation of the Florida Keys National Marine Sanctuary, the National Oceanic and Atmospheric Administration brought representatives of user groups and the public together with federal and state agency officials to assemble an integrated coastal management plan.*

Bohnsack JA. 1993. Marine reserves: They enhance fisheries, reduce conflicts, and protect resources. Oceanus 36(3):63-71. *Humankind has the ability to catch fish faster than they are produced and there is a need to develop ways of preventing overfishing and resource depletion. Marine fishery reserves, areas protected from all fishing and other harvesting activities, provide one approach.*

Bohnsack JA. 1998. Application of marine reserves to reef fish management. Aust J Ecol. 23(3):298-304. *Sufficient evidence is available to justify the expanded use of marine reserves in an adaptive approach to fisheries management.*

Carpenter KE, Abrar M, Aeby G, Aronson RB, Banks S, Bruckner A, Chiriboga A, Cortes J, Delbeel JC, DeVantier L, et al. 2008. One third of reef-building corals face elevated extinction risk from climate change and local impacts. Science 321 (5888):560-563. *Declines in abundance of corals are associated with bleaching and diseases driven by elevated sea surface temperatures, with extinction risk further exacerbated by local-scale anthropogenic disturbances.*

Committee on the Evaluation, Design, and Monitoring of Marine Reserves and Protected Areas in the United States, Ocean Studies Board, National Research Council. 2001. Marine Protected Areas: Tools for Sustaining Ocean Ecosystem. Washington, DC: National Academies Press. 288 p. *A controversy persists over the value of no-take marine preserves because we lack a scientific consensus on the optimal design and use of reserves and have only limited experience in determining the costs and benefits relative to more conventional management approaches.*

Ehler CN, Basta DJ. 1993. Integrated management of coastal areas and marine sanctuaries. Oceanus 36(3):15-18. *A call for the development of comprehensive management plans for marine areas.*

Grober-Dunsmore R, Keller BD (eds.). 2008. Caribbean connectivity: Implications for marine protected area management. Proceedings of a Special Symposium, 9-11 November 2006, 59th Annual Meeting of the Gulf and Caribbean Fisheries Institute, Belize City, Belize. Marine Sanctuaries Conservation Series ONMS-08-07. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Office of National Marine Sanctuaries, Silver Spring, MD. 195 pp. *A collection of scientific papers on aspects of the connectivity of tropical marine ecosystems in the Caribbean region. Geographic areas are inextricably linked through the movement of pollutants, nutrients, diseases, and other stressors, which threaten to further degrade coral reef communities.*

Hemond EM, Vollmer SV. 2010. Genetic diversity in the threatened staghorn coral (*Acropora cervicornis*) in Florida. PLoS ONE 5(1)e8652.doi:10.1371/journal.pone.0008652. Available from: http://www.ncbi.nlm.nih.gov/pubmed/17158464 (Accessed 22 Apr 2011). *Conservation efforts for staghorn coral should focus on maintaining and managing populations locally, rather than relying on larval inputs from elsewhere.*

Huang D. 2008. Assisted colonization won't help rare species. Science 322(5904):1049. *Many coral species are rare or uncommon and there is little fundamental knowledge on the biology of many of those species. It is hard to imagine that assisted colonization will significantly help the recovery of rare species.*

Lester SE, Halpern BS, Grorud-Colvert K, Lubchenco J, Ruttenberg BI, Gaines SD, Airamé S, Warner RR. 2009. Biological effects within no-take marine reserves: a global synthesis. Mar Ecol Prog Ser. 384:33-46. *Despite variability, positive responses are far more common than no differences or negative responses, validating the potential for well designed and enforced reserves to serve as globally important conservation and management tools.*

Overpeck JT, Weiss JL. 2009. Projections of future sea level becoming more dire. P Nat Acad Sci. 106:21461-21462. *A prediction of how sea level will change this century and beyond.*

Susman D, Sivlani M, Milon J. 1999. Perceptions and attitudes regarding marine reserves: A comparison of stakeholder groups in the Florida Keys National Marine Sanctuary. Ocean Coast Manage. 42:1019-1040. *An analysis of the user groups of marine waters in the Florida Keys.*

Wilkinson C. (ed.). 2008. Status of Coral Reefs of the World: 2008. Townsville, Australia. Global Coral Reef Monitoring Network and Reef and Rainforest Research Center. 304p. *Nineteen percent of reefs were found to be totally degraded in 2008, down from 20% in 2004, while 15% are threatened with immediate collapse within 20 years and 20% in the longer term (20-40 years), totaling 54%. In 2004, this figure was 70%. The remaining 46% of reefs are not threatened by local impacts but could be vulnerable to climate change and ocean acidification.*

Website references

Alban F, Appéré G, Boncoer J. 2008. Economic Analysis of Marine Protected Areas. A Literature Review. EMPAFish Project (European Marine Protected Areas as tools for Fisheries management and conservation), Booklet No. 3. Editum. 51 p. Available from: https://www.um.es/empafish/files/Deliverable%205-New%20version.pdf (Accessed 28 Apr 2011). *A review of the socioeconomic literature dedicated to various aspects of marine protected areas related to ecosystem preservation, fisheries management, recreational activities, and distributional consequences of marine protected areas.*

Davidson K. 2003. Coral reefs doomed, study says / Centuries of overfishing killing ecosystems. SFGate.com. Available from: http://articles.sfgate.com/2003-08-16/news/17503462_1_coral-reef-coral-diseases-reef-ecosystems (Accessed 27 Apr 2011). *Experts warn that because they have been pummeled by overfishing, the world's coral reef ecosystems will not survive for more than a few decades unless drastic action is taken to protect them.*

National Oceanic and Atmospheric Administration, National Marine Protected Areas Center. Case Studies: Florida Keys National Marine Sanctuary. Available from: http://www.mpa.gov/helpful_resources/florida_keys.html (Accessed 28 Apr 2011). *The popularity of the Florida Keys led to pollution of the marine ecosystem and overuse of resources. Signs of anthropogenic degradation in the Keys included damage to corals and degrading water quality. It was recognized that protection measures needed to be implemented before the resources were damaged beyond repair.*

Science Daily. 2008. Exploited fish make comeback in world's largest no-take marine reserve network. Science Daily, June 25, 2008. Available from: http://www.sciencedaily.com/releases/2008/06/080623125012.htm (Accessed 27 Apr 2011). *Numbers of coral trout were significantly*

Human Connections

higher in no-take reserves than in sites that remained open to fishing in four of five offshore regions and two of three inshore regions of the Great Barrier Reef.
Shipp RL. No take marine protected areas (NMPAs) as a fishery management tool, a pragmatic perspective. Available from: http://www.seafriends.org.nz/issues/war/shipp.htm (Accessed 27 Apr 2011). *MPAs (both "no take" and other types) can serve a positive function as a management tool in protecting breeding aggregations, in helping recovery of severely overfished and unmanaged insular fish populations with little connectivity to adjacent stocks, and in protecting critical habitat which can be damaged by certain fishing methods.*
Smith JW. 2010. Coral Reef Loss: Determining the Importance of Overfishing and Nutrient Pollution in the Global Decline of Coral Reefs. National Center for Ecological Analysis and Synthesis. Available from: http://www.nceas.ucsb.edu/featured/smith (Updated 24 Aug 2010, accessed 27 Apr 2011). *Discussion of factors that lead to a phase shift in coral reefs.*
South Florida National Park Trust. Our Parks. Available from: http://www.southfloridaparks.org/parks.html (Accessed 27 Apr 2011). *Four of our nation's most spectacular national parks are located in south Florida.*
The Encyclopedia of Earth. 2010. Florida Keys National Marine Sanctuary. Available from: http://www.eoearth.org/article/Florida_Keys_National_Marine_Sanctuary (Updated 22 Jan 2011; accessed 28 Apr 2011). *Summary of the history of preservation efforts of the coral reefs of Florida.*

Index

C

D

E

F

G

H

I

J

K

N

O

P

Q

R

S

T

U

V

W

Y

Z

"If you love south Florida's marine environment, then read Tropical Connections and share it. If you are not familiar with this ecosystem, then get acquainted through the copious illustrations, clear writing, and comprehensive summaries. The book does a fine job at distilling complex science for the non-specialist."

Dr. R. Eugene Turner, Professor
Louisiana State University

"This work is very timely in that it addresses a unique environment of the United States that is under severe pressure because of activities related to human development. This book is effective in documenting the dramatic changes in south Florida over the last few decades in a format that is very attractive and easy to read."

Dr. Paul A. Montagna, Professor
Texas A&M University

"This is a wonderfully accessible yet exhaustively researched book and I really like the quality and the abundance of the illustrations. To say it covers the key issues is a serious understatement. I think Tropical Connections will stand for quite a while as a milestone."

Dr. John Ogden, Former Director
Florida Institute of Oceanography

"Tropical Connections is a wonderful summary of the varied facets that influence south Florida's marine environment. The editors have brought together environmental experts from a variety of backgrounds to lend their talents to present a thorough understanding of the south Florida marine ecosystem."

Dr. Stephen A. Bortone, Executive Director
Gulf of Mexico Fishery Management Council

"Tropical Connections is the culmination of an unprecedented effort to assemble a summary of the status and threats to south Florida habitats. My hope is that this book will serve as a call to action to residents, outdoor enthusiasts, environmentalists, educators, and policymakers alike to embrace a stewardship ethic that protects our natural heritage for present and future generations."

Anne Morkill, Wildlife Refuge Manager
U.S. Fish and Wildlife Service

ISBN: 978-0-9822305-3-4