Spatial distribution of benthic microalgae on coral reefs determined by remote sensing

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This thesis is formatted for publication to Coral Reefs, subsequently tables and figures are attached after the text. Further information and pictures are available in the appendices and a table of contents is attached for the purpose of the thesis.

I declare that this thesis does not contain any material which has been submitted by me previously for any other degree or diploma to any university, and to the best of my knowledge, it does not contain any material published or written by another person, except where the due reference is made in the text.

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Abstract

Benthic microalgae have recently been identified as a highly productive component of coral reef ecosystems. Understanding the ecological role of benthic microalgae, however, requires information on its spatial distribution patterns. The large surface area of coral reefs that benthic microalgae can occupy creates challenges for effectively and efficiently measuring their distribution. Remote sensing techniques were applied to identify the spatial extent of benthic microalgae on Heron Reef in the southern Great Barrier Reef, Australia. Field sampling involved chlorophyll analysis and reflectance measurements of sediments at 55 sites. Reflectance of benthic microalgae was measured in spectral bandwidths corresponding to those measured by the Thematic Mapper sensor on the Landsat satellite, which was used to acquire the remotely sensed image in this study. Measured chlorophyll concentrations (23 to 1153 mg Chl *a* m^{-2}) were classified into three classes using a K-means of clustering algorithm (1–170, 171–290 and 291+ mg Chl *a* m^{-2}). Chlorophyll and spectral measurements were used to produce spectral signatures for the three chlorophyll classes. Field sampling was synchronized with the regular overpass of the Landsat Five satellite. The remotely sensed image was classified into the same three classes based on benthic microalgal chlorophyll and reflectance field measurements. A geographical information system was useed to visualise the classification and calculate the biomass of benthic microalgae for Heron Reef. The classification revealed large-scale patterns with high values in the lagoon and on the windward side of the reef, and low values on the leeward side near Heron Island. This ubiquitous distribution identifies benthic microalgae as a large component of the total benthic chlorophyll at Heron Reef, and therefore has a key role in primary productivity of that ecosystem. Remote sensing techniques have proven to be an effective and efficient method for examining the spatial distribution of benthic microalgae.

Key words: benthic microalgae, coral reef, chlorophyll , distribution, productivity, classification, spatial variation, remote sensing, Heron island

Introduction

Benthic microalgae are dominated by unicellular plants, e.g. diatoms (*Bacillariophyta*), dinoflagellates (*Dinophyta*) and some filamentous cyanobacteria (*Cyanophyta*) (Jeffrey *et al.* 1997, MacIntyre *et al.* 1996, Clayton and King 1994). They inhabit the top few centimeters of the substrate layers (mud or sand) of marine sediment, given sufficient light for photosynthesis (MacIntyre *et al.* 1996, MacIntyre and Cullen 1996,Charpy and Charpy-Roubaud 1990). Benthic microalgae have an important role as a food source for higher trophic levels in shallow water foodwebs (Heil *et al.* in review, MacIntyre *et al.* 1996, Sorokin 1991, Charpy and Charpy-Roubaud 1990, Revsbech *et al.* 1981). The cohesive capacity of the benthic microalgae reduces erosion of sediment layers, therefore affecting the construction and destruction of benthic habitats (Miller *et al.* 1996, Williams *et al.*1985).

Coral reefs generally experience low nutrient conditions, increases of which can have deleterious effects (Hatcher 1997, Brown 1997). Benthic microalgal biomass can be influenced by nutrient addition (Heil *et al.* in review, MacIntyre *et al.* 1996). The response of benthic microalgae to nutrients has potential to be used as a bioindicator to determine the susceptibility of coral reef ecosystems to added nutrients. The significance of benthic microalgae in relation to for instance productivity of corals and macroalgae depends on different factors such as biomass and spatial extent. The spatial distribution and biomass of benthic microalgae has previously been determined for shallow marine systems, using pigment analyses (Light and Beardall 1998, Heil *et al.* in review, Jeffrey *et al.* 1997). Benthic microalgae generally consist off chlorophyll *a*, *c* and carotenoids (Jeffrey *et al.* 1997, Clayton and King 1994, Rowan 1989).

Phytoplankton biomass and spatial extent, characterised by chlorophyll *a* concentrations, has previously been determined using remote sensing techniques (Yoder 1998, Yacobi *et al.* 1995, Alberotanza 1992). Remote sensing has been shown to be an effective technique, with increasing use, in the marine environment (e.g. coral reefs) for mapping and discriminating surface cover (e.g.

corals and macroalgae) (Chauvaud *et al.* 1998, Holden and LeDrew 1998, Mumby *et al.* 1997, Ahmad and Neil 1994, Luczkovich *et al.* 1993, Jupp *et al.* 1985). Remote sensing reduces the time and effort in obtaining large amounts of data directly from the field, particularly in marine environments that are often remote and difficult to access (Holden and LeDrew 1998).

It has been shown that there is a relation between the reflectance of marine vegetation in specific wavelengths and absorption of light by its pigments (Paterson 1998, Bajjouk *et al.* 1996, Aitken and Borstad 1995). Therefore it is expected that knowledge of these pigments will be essential for determining the correct radiometric signatures for benthic microalgae in order to be detected by a remote sensor. When using remote sensing techniques it is important to understand the physical characteristics and limitations caused by the atmosphere and the water layer (Jupp *et al.* 1996, Kirk 1994, Lyzenga 1981). Discrimination of submerged benthic features by their apparent reflectance, will be affected by solar geometry, waterdepth, location, turbidity, organic and inorganic contents of the water column (Bierwirth *et al.* 1993, Goetz 1992, Alberotanza 1992, Lyzenga 1981, Jerlov 1976).

Thus far, no published work has been noted on techniques for mapping the extent and quantity of benthic microalgae within a coral reef. Therefore, this study aims to firstly, determine the spectral signature (reflectance / absorption in different bandwidth) of benthic microalgae in shallow sediment areas of a coral reef; and secondly, map the spatial distribution of benthic microalgae of Heron Reef using a remotely sensed image.

Methods

Heron Reef (23°25'S, 151°55'E) which is part of the Capricorn-Bunker group located in the southern Great Barrier Reef, Australia. This site was chosen due to available image data (Landsat Thematic Mapper and aerial photographs), accessibility through the Heron Island Research Station and previous research conducted in the area (Heil *et al.* in review, Ahmad and Neil 1994, Groves 1993, Jupp 1985).

Heron Reef is a lagoonal platform reef of 28 km^2 (10 km east-west by 4 km north-south) containing a coral cay (0.2 km^2) located on the western edge (Fig. 1) (Groves 1993). The diurnal tidal range during the sampling period was approx. 2.3 m. The prevailing wind was south-easterly.

Fifty-five sampling sites on nine transects (1000 m length) were established around the reef and divided over four different area types (Fig. 2). Sample sites on the east side of the reef (lagoon area) were only accessible by motorboat during high tides. Low tide was used to collect samples by foot in the shallow area of the reef flat and the gutter. Geographical coordinates using a Global Positioning System were determined at each site to relate the field data to a georeferenced remotely sensed image.

At each site benthic microalgae sediment cores were collected and spectral reflectance was measured (Fig. 3). Benthic microalgal pigments and reflectance values were determined and K-means clustering was used to establish chlorophyll *a* classes (Fig. 3). Field sampling was timed with the overpass of the Landsat Thematic Mapper on the 3rd of March 1999 (Fig. 3). The Landsat image was corrected, enhanced and then classified using the pigment and reflectance values obtained from the sample sites (Fig. 3). A geographical information system was used to produce maps and calculate area cover (Fig. 3). Before explaining each method in more detail, the remote sensing process will be further explained.

Remote sensing technique

The methodology (Fig. 3) applied in this study relates remote sensing with field based measurements (Holden and LeDrew 1998). The sun is the major source of electromagnetic radiation transmitted, absorbed, and/or reflected depending on the pathway by different mediums (e.g. atmosphere and water) and substrates (e.g. sediment). The influence on the radiation, by a medium and/or substrate depends on the wavelength of incident electromagnetic radiation in relation to the size, density and chemical constituents of the medium or substrate. The water column, for example, will absorb infrared wavelengths, but wavelengths in the blue part of the spectrum will be transmitted through this medium (Jupp *et al.* 1996, Jensen 1996, Curtiss 1994, Lemmens 1987, Lyzenga 1986, Jerlov 1976). Radiation can be measured using a radiometer, which can be handheld for use in the field to measure individual areas or mounted on a satellite to produce a remotely sensed image.

The quantity and quality of the reflected signal of sunlight from the substrate received by the radiometer depends on the wavelength, the kind of substrate and the transmission through the mediums. The radiometer receives radiation of certain bandwidths. By correcting this received signal for atmospheric constituents and water column depth is it possible to characterise the type of substrate by its reflectance value (Paterson *et al.* 1998, Jensen 1996, Curtiss 1994, Alberotanza 1992, Lemmens 1987). Hence, by measuring both the amount of benthic microalgae in the reef sediment and its characteristic reflectance values for the different bands (signature), a relationship between variation in benthic microalgae and reflected electromagnetic radiation can be estimated.

Remotely sensed images consist of ground resolution elements. A small ground resolution element (high resolution) will register smaller details in the remotely sensed area, and therefore the choice depends on the information required (Atkinson and Curran 1997). Each ground resolution element in the area measured by the radiometer is determined by its field of view, in a set bandwidth for the Landsat Thematic Mapper which is 30 x 30 m. This sensor was chosen for this study because of the availability of the data. The Landsat Thematic Mapper images consist of a ground resolution element grid area of 185 x 185 km (Jensen 1996). The Landsat Thematic Mapper sensor is capable of detecting signals in blue (450–520 nm), green (520–600 nm), red (630–690 nm) and Near Infra Red (NIR) (760–900 nm) bands and has a swath width of 185 km, instantaneous field of view of 30 x 30 m and a temporal resolution of 16 days (Jensen 1996).

By determining the reflectance values in the different band characteristics of benthic microalgae and correcting for the atmosphere and water column it is possible to examine each image ground resolution element and estimate benthic microalgal concentrations.

Benthic microalgal sediment concentration

To determine the concentrations of benthic microalgae three replicates of 3 ml sediment cores were collected at each sample site using a 10 ml cut off syringe, which was pushed into the sediment. The sediment was ground up in analytical reagent grade acetone and the total volume made up to 10 ml with acetone and placed in centrifuge tubes. Tubes were wrapped with aluminum foil and placed in the freezer for two hours to extract the pigments (chlorophyll and carotenoid). Samples were centrifuged at 3000 revolutions per minute, for 25 minutes. Sub-samples of supernatant were placed in a spectrophotometer to measure absorbence at: 358 nm (Bacterial chlorophyll *a),* 480 nm (carotenoid), 510 nm (carotenoid), 630 nm (chlorophyll *c*), 647 nm (chlorophyll *b*), 664 nm (chlorophyll *a*), and 750 nm (Turbidity). Results were used to estimate the concentration of chlorophyll *a, b* and *c* and carotenoid (mg m^{-2})(Heil *et al.* in review, Parson *et al.* 1996*).*

Benthic microalgal class determination

To classify the areas with similar benthic microalgal levels the classes of the chlorophyll *a* concentrations had to be determined by using K-means clustering algorithm, STATISTICA software. The algorithm results in clusters or groups of sample points that have a characteristic mean chlorophyll *a*, standard deviation and number of samples within each cluster. After analysing these values the rounded class borders were designed by adding or subtracting twice the standard deviation of the mean chlorophyll *a* value within the cluster formed by the classes.

The assumption that the chlorophyll *a* values are normally distributed within a cluster was checked graphically. The class borders were adjusted to rounded class borders for the classes were not overlapping.

Benthic microalgal field radiometry

At each study site reflectance was measured using a portable battery powered Exotech, 100 - C radiometer. The radiometer measured the reflected radiance of a substrate using the same bands used by the Landsat Thematic Mapper sensor (Curtis *et al.* 1994, Milton 1987). Reflected substrate radiances were measured within 1 m of the area where the sediment samples were taken.
The influence of water on the reflected radiance of the sediment was determined by measuring benthic microalgae with and without water on top (an area of 20 x 30 cm of the first 3.0 cm of sediment was scooped of the bottom surface and placed above the water). Radiance was measured by placing the handheld radiometer approximately 0.5 m above the sediment sample and above the water surface with the sediment below. During each series, radiance of a Spectron (approximately lambertian) calibration plate was measured, to act as a surrogate for irradiance (Milton 1987). Reflectance (radiance/irradiance) was calculated by dividing sample radiance values by irradiance values from calibration plate at closest point in time, producing unit less reflectance.

Benthic microalgal reflectance and concentrations

The relationship between benthic microalgal concentration and reflectance value was established using K-means of clustering. By classifying the chlorophyll *a* values (using the K-means clustering results) it is possible to classify the related reflectance values. This was applied to the reflectance measured from the sediment with and without water on top.

Patches of benthic microalgae were visible on the reef as a difference in colors. To determine the relationship between green/brown and white patches on the reef, their reflectance, an intensive sampling site was established on the north east side of the island (Fig. 1), with three replicates for each site. Sediment and reflectance samples were taken from 5 sites in the green/brown and in the white patches. The mean reflectance and pigment values were calculated for each area type.

Image acquisition and enhancement

The satellite image used in this study was an uncorrected subset of the Landsat Thematic Mapper scene (path 90, row 76) recorded at 9:30 am local time on the 3rd March 1999 provided by the Australian Centre for Remote Sensing. The scene consists of Heron Reef and several other reefs of the Capricorn Bunker group. The blue, green and red bands were selected because of their water penetrating characteristics. It is known that the depth penetration of Type II water (a classification based on optical properties), present at Heron Reef, are about 30 m for blue, 18 m for green and 5 m for the red band (Ahmad and Neil 1994, Jupp 1988, Jerlov 1976).

The first step of the pre-processing phase was image rectification. Co-ordinates of stable natural feature control points were identified from a georeferenced Landsat Thematic Mapper image of the Capricorn Bunker group area from 16th October 1997 to geometrically correct to Universal Transform Mercator projection and Australian Geodetic Datum 1984. The Heron Reef subset was radiometricaly corrected for additive path radiance by applying dark pixel subtraction (Jensen 1996). ERDAS imagine software was used for pre processing and image enhancement (Jensen 1996, Lemmens 1987).

Arcview geographic information system package was used to digitise the extent of the study area. The digitised extent was used to mask out the areas not used for classification, (Heron Island, surrounding deep waters and the reef crest). Areas covered by clouds will affect the information about the area. They are the image characterised by pixels with extremely high reflectance values in the red band, and were therefore filtered out (Jensen 1996, Curtiss 1994).

Distribution of non-benthic microalgal substrates

The spatial resolution of the Landsat scene was 30 x 30 m, hence, it is important to understand that this pixel is formed not only by the reflectance of the benthic microalgae but also by the coral and algal cover. Therefore cover estimates had to be made to understand how much of the pixel value will be resulting from the benthic microalgae. To determine the cover estimate, the study area was divided in to four different sections depending on their characteristics (Fig. 2). Cover estimates were determined by three 50 m line transects (along reef flat and gutter) and from aerial photographs, at scale of 1:2400 (for lagoon, lagoon edge and reef crest).

The four different areas (Fig. 2) were chosen due to their sediment distribution characteristics, coral or macroalgal cover and depth, since these will influence the signature of one pixel in the image. Areas that were not included in this study were areas of low sediment cover and areas where water was too deep to use the red band of the remote sensor (Ahmad and Neil 1994, Jupp 1985) (Fig. 2).

Benthic microalgal image classification

The chlorophyll *a* classes were used to group the values of all the different sample sites and analyse image elements with similar reflectance by overlaying the classified sites (training sites) on top of the image and extract the representative reflectance values. Training sites were areas in which spectral characteristics were assumed homogenous. Bathymetry of these sites was used to subdivide the chlorophyll *a* classes into shallow or deep categories thereby taking into account influences caused by the water column. The spectral signature of the benthic microalgal training sites was compared visually with the signatures resulting from the field radiometry (Jensen 1996, Curtiss 1994). Field observations and aerial photographs were used to determine other substrate types to be identified in the image. When all signatures and cover types were determined, the image was classified using a minimum-distance to means algorithm (Jensen 1996).

Separability and divergence, using the “error matrix” and divergence test express accuracy of the classification. It describes the relationship between the reference data appointed by the training sites and the resulting classified image data. The interpretation of the error matrix is explained in Appendix A.

The result of the classification was compared with the field observations, aerial photographs and the operator's knowledge of field sites and separability of the classes was analysed. An iterative process was conducted repeating the method of supervised classification. The iteration was influenced by the quality analysis of the classification and by using different K-means clustering results.

Georeferenced benthic microalgal sediment samples from previous studies were planned to be utilised for validating the classified image but due to inaccuracies in their position this was discarded and a final quality control is still needed to verify the accuracy of the classification.

Benthic microalgal mapping and analyses

With Arcview it was possible to calculate the surface area for each polygon. The surface areas of the benthic microalgal patches were summed to calculate the total surface area per chlorophyll *a* class. Geographical information system was also used to develop a map of the study area (Fig. 1) and maps of the classified images (Fig. 7 & 8) (Earth Systems Research Institute 1998).

The calculated benthic microalgal areas had to be unmixed with the unmixing factor. This factor contributes to the fact that the classified benthic microalgal pixel also has some coral and macroalgae. The unmixing factor is therefore resulting from average percentage of cover type for each of the areas types (Table 1) in combination of an estimated size of the area types. By applying the unmixing factor on the calculated areas of the benthic microalgae their areas size will reduce and the area size of coral and macroalgae will enlarge.

Average chlorophyll *a* concentrations were estimated for the cover types (coral, macroalgae and turf algae) using chlorophyll *a* values from the literature (Klumpp and McKinnon 1989, Carpenter 1985, Odum 1958) and percentage cover type for the different areas. The resulting value was applied to calculate the percentage that the benthic microalgae is contributing to the total chlorophyll *a* quantities of the substrate on Heron Reef.

Results

Benthic microalgal concentration and classification

Benthic microalgal pigment distributions for the different sites in the study area were grouped into the four areas types (Fig. 4). Chlorophyll *a* values varied from 36 to 1153 mg m^{-2}, chlorophyll *c* from 3 to 116 mg m^{-2}, Bacterial chlorophyll *a* from 7 to 104 mg m^{-2} and carotenoid from 19 to 286 mg m^{-2}. Chlorophyll *b* values were discarded since they had mostly zero values (as was expected for benthic microalgae). This process found that chlorophyll *a* values were higher (ANOVA, $p<0.05$) than other pigments in the study area and therefore they have most influence on estimating the biomass.

The highest concentrations of chlorophyll *a* were found in the lagoon edge area (Fig. 4). Relatively high concentrations were measured in the gutter area in comparison with the surrounding reef flat. Other pigment concentrations relative to chlorophyll *a* values were evenly spread over the different areas. The exception, however, was the gutter area, which had a high chlorophyll *c* and bacterial chlorophyll *a* (ANOVA, $p<0.05$) in comparison with other reef areas. K-means of clustering was used to group the chlorophyll *a* (benthic microalgae) which resulted in three classes; 1 - 170, 171 - 290 and 291+ mg Chl *a* m^{-2} (Table 2).

Benthic microalgal reflectance signature

The sediment reflectance values at each site were classified depending on site specific chlorophyll *a* value and the three classes. The reflectance values of the sediment were divided into two groups, one group measured from substrate with water (Fig. 5a) and one group without water (Fig. 5b). The average depth of the water layer was ~1.4 m. Average chlorophyll *a* reflectance signature of bare substrate without water was higher than that of the substrate with the water layer on top (MANOVA, $p<0.05$). From this it can be concluded that the water layer was influencing the electromagnetic radiation. Reflectance values were lower when measured with water in between, due to the scattering and absorbing effect of water (Fig. 5a & 5b). There was a difference between the signature of the three chlorophyll *a* classes (MANOVA, $p<0.05$) (Fig. 5a & 5b). Low concentrations of chlorophyll *a* showed higher reflectance. Although the water layer was influencing the signal it was still possible to distinguish the differences between chlorophyll *a* concentrations in shallow water. No difference in reflectance values of the near infra red band between the different chlorophyll *a* classes was evident (Fig. 5a & 5b). Therefore the near infrared band was discarded for further classification purposes.

No difference in benthic microalgal biomass was detected between green/brown (77 mg Chl *a* m^{-2}) and white (66 mg Chl *a* m^{-2}) sediments patches (ANOVA, $p>0.05$) (Fig. 6a). However, the spectral signatures of the areas discerned the visual difference (ANOVA, $p<0.05$) (Fig. 6b). This need to be taken into consideration when interpreting remotely sensed benthic microalgal signatures.

Image enhancement and classification

In comparison with a cloud free 1997 Landsat Thematic Mapper image (Fig. 7) the image used in this study was partially covered by clouds (11% of the study area) and shadows (9% of the study area)(Fig. 8). Removing pixels with extremely high values in the red band filtered out most of the dense clouds. Disturbance caused by shadows were removed with help the classification process. The separability of the classes within the training sites was determined using the Transformed Divergence distance measure (Jensen 1996). This resulted in an average divergence of 1742 (ranging between 0 min. – 2000 max. separator) which according to Jensen (1996) is poor between class separation.

The error matrix (Table 3) shows an overall accuracy of 62%. The general trend of the error matrix was for a larger quantity of reference data and higher accuracy of values in the non-benthic microalgae rather than in the benthic microalgal categories. To obtain a large sized reference data set, to make it more reliable, almost all the sample sites were used as training sites, resulting in a biased estimate of the accuracy. Reference data for the different categories showed that training sites in the low and high classes of benthic microalgae had higher quantities then in the medium categories of benthic microalgae. Within benthic microalgal classes the highest user accuracy was found in the shallow 1 - 170 mg

m^{-2} (63%) and the deep 290+ mg m^{-2} (82%) Chlorophyll *a* classes. This shows there is confusion between the 1 - 170 mg m^{-2} chlorophyll *a* class and the 171 - 290 mg m^{-2} and the 290+ mg m^{-2} class and the medium chlorophyll *a* class. This can be interpreted as the middle class being a transition class between low and high chlorophyll *a*.

Spatial extent of benthic microalgae

From the classified Landsat image (Fig. 8) it can be seen that the west part of the study area consisted of large areas with low chlorophyll *a* values. High values were found in the lagoon and on the windward side of the reef. These large scale patterns were produced consistently as the products from the iterative process of the classification, indicating the reliability of these patterns.

The clouds and shadow resulting areas caused small disturbances on the edges of those areas. This is due to the fact that the edges are irregular as a result of thin cloud cover surrounding the clouds. In the deep part of the lagoon there were some areas, which were not classified as benthic microalgae, probably due to water column effects which produced reflectance signatures similar to the non benthic microalgal classes. When interpreting the classification these disturbances have to be considered.

A pixel identified as 100% benthic microalgae resulting from the classification had to be unmixed using the calculated unmixing factor of 77% benthic microalgae since the pixel area had for 23% of corals or macroalgae. This factor was obtained results from the estimated distribution of benthic microalgae and corals or macroalgae within the study area. After the applying the calculated unmixing factor the vegetation cover could be calculated. The study area occupied 20 km^2 (72% of Heron Reef) of which, 45% of the Heron Reef classified as corals (dead or life) and/or macroalgae and 54% classified as benthic microalgae (18% 1 - 170 mg Chl *a* m^{-2}, 12% 171 - 291 mg Chl *a* m^{-2} and 13% 291+ mg Chl *a* m^{-2}) and 11% was benthic microalgae resulting from the areas covered by clouds and shadow (Fig. 9).

With the calculated surface areas total Chlorophyll *a* biomass (19312 kg, Table 4) as an indicator for productivity was determined for the substrate of Heron Reef. Although the mg Chl *a* m^2 of benthic microalgae low in comparison with the corals and macroalgae it still had a 20% influence on the total chlorophyll *a* amount of Heron Reef. This is primarily due to the relative size of the benthic microalgal area.

Discussion

Benthic microalgal distribution on Heron Reef was determined by measuring chlorophyll *a* concentration of the sediment and relating this to remotely sensed data using Landsat Thematic Mapper imagery. The discussion will be structured into the following sections: benthic microalgal distributional patterns, benthic microalgal productivity, remote sensing techniques, technique development, conclusions.

Benthic microalgal distributional patterns

The range of benthic microalgal concentrations measured in Heron Reef sediments in the present study (32 - 1153 mg Chl *a* m^{-2}) is similar to that measured previously (92 - 995 mg Chl *a* m^{-2}; Heil *et al.* in review). The more extensive sampling conducted in the present study (165 samples), combined with the limited sampling (81 samples) in the previous study (Heil *et al.* in review) supports the observation that chlorophyll a concentrations measured in Heron Reef sediments are amongst highest reported for any marine sediments.

Large scale distributional patterns in benthic microalgal chlorophyll concentrations were evident in both the field samples and the remote sensing image classified for chlorophyll concentrations. Higher concentrations of benthic microalgae (>170 mg Chl *a* m^{-2}) were observed on the windward (southeast) area of the Heron reef platform in both the lagoon and lagoon edge sediments. Lower concentrations (<170 mg Chl *a* m^{-2}) were more common on the leeward (northwest) area of the Heron reef platform, particularly near Heron Island. Large scale patterns of remotely sensed features of Heron reef platform have been previously described (Ahmad and Neil 1994), however, this previous remotely sensing interpretation did not include benthic microalgae.

The overall pattern of benthic microalgal distribution is similar to large scale patterns of various features of the calcareous sediments; a) sediment grain size, b) proportion of green algae (*Halimeda* spp.) skeletal material, and c) proportion of coralline algae skeletal material (Groves 1993). High benthic microalgal concentrations corresponded to areas with small sediment grain size (< 0.5 mm diameter), and high proportions of sediments derived from *Halimeda* spp. (10-20%), coralline algae (20-40%) (Groves 1993). This correspondence in benthic algal distributions and sediment features may be due to sediment features controlling benthic microalgal distributions. Benthic microalgal patchiness is often related to sediment texture and relief (MacIntyre *et al.* 1996, Yager *et al.* 1993, Jorgensen and Revsbech 1983). Alternatively, environmental conditions promoting the deposition of small, *Halimeda* spp. and coralline algae-rich sediments also promotes high concentrations of benthic microalgae. Sediment depositional environments are strongly influenced by water motion regimes and water depth, factors that can influence benthic microalgae (Delgado *et al.* 1991, Yallop *et al.* 1994). Fine grained sediments are more nutrient-rich than coarse grained sediments (Hansen and Alongi 1991), and higher concentrations of benthic microalgae could be related to higher nutrient availability. While nutrient enrichment studies have not generally stimulated benthic microalgal biomass (MacIntyre *et al.* 1996, Sundback *et al.* 1991), nutrient enrichments on Heron reef sediments did stimulate benthic microalgae, perhaps due to the low ambient nutrient environment (Heil *et al.* in review).

Large scale distributional patterns of benthic microalgae have been established for various temperate and sub-tropical sites; Port Phillip Bay (Light and Beardall 1998), Moreton Bay (Abal *et al.* 1998). Water depth, and by inference, light availability has been interpreted as a dominant factor in these distributional patterns. Unfortunately, comparable distributional patterns of other reef systems have not been located. Thus, the ability to infer the causal relationships that create the pattern observed on Heron Reef is limited.

Small scale distributional patterns in benthic microalgae are also evident (Paterson *et al.* 1998, MacIntyre *et al.* 1996, Yallop 1981). Visibly discolored sediments (green/brown) were observed in patches from < 1 m^2 to 10s of m^2, distinguished from the generally white colored calcareous sediments. This coloration of sediments was due to benthic microalgae at the sediment surface (Heil *et al.* in review); similar found in other locations (MacIntyre *et al.* 1996). However, visibly green/brown sediments had slightly higher but not significantly ($p > 0.05$) higher benthic microalgal pigment concentrations than white sediments in the present study (Fig. 6a). This lack of correlation of coloration with pigment concentration is likely due to the relative position of benthic microalgae in the sediments. Higher benthic microalgal concentrations in surface sediments are more visible to both human observers and remote sensing sensors, but the total benthic microalgae concentration integrated through the top 3 cm of sediments is not visible. Vertical migration of benthic microalgae within the top several cm of sediment has been observed (MacIntyre *et al.* 1996). The processes that control vertical migration of benthic microalgae are unclear, but suggestions of light, grazing and rainfall affects on benthic microalgae have been made (Paterson *et al.* 1998)

Benthic microalgal productivity

Coral reefs are among the most productive ecosystems on the planet (Chisholm and Barnes 1998, Hatcher 1997a/b). Primary productivity estimates of coral reef environments using changes in dissolved carbon dioxide and/or oxygen concentrations in water flowing over a reef integrate all primary producer components (Chisholm and Barnes 1998, Odum and Odum 1955). The contribution of benthic microalgae to this overall production has been either ignored or underestimated. Sandy sediments are generally not considered a net primary producing area of coral reefs, however, the high chlorophyll concentrations, oxygen evolution and PAM fluorescence of coral reef sandy sediments indicate they contribute largely to total reefal productivity, particularly given the large area of sand typical of coral reefs (Heil in review).

The spatial extent of the productivity on Heron Reef has been estimated using remote sensing (Ahmad and Neil 1994). The Ahmad and Neil (1994) classification was carried out with the aid of canonical variate analysis and minimum spanning trees (Gower and Ross 1969). The estimation of primary productivity is based on the relationship between increasing primary production and increasing second canonical variate developed in terrestrial environments (Ahmad and Neil 1994). Using these techniques, there was low or no productivity in the sandy sediment area of Heron Reef. Productivity by the benthic microalgae were not detected, however sediment chlorophyll *a* concentrations are correlated with benthic microalgae productivity (Paterson *et al.* 1998, Pinckey 1994) and high chlorophyll a concentrations were measured in the present study. Although the average amount of chlorophyll *a* for benthic microalgae is not high in comparison with coral and macroalgae, it contributes at least 20 % to the total amount of chlorophyll *a* on the Heron Reef platform. Thus the "Secret garden" (MacIntyre *et al.* 1996) of benthic microalgae could be a major contributor to productivity of coral reefs.

Remote sensing technique

When interpreting the classified Thematic Mapper image in relation to the distribution of the benthic microalgae, it is important to consider its adjusted accuracy (62 %) in comparison to similar studies. Classification of a coral reef habitat in 13 fine classes using Thematic Mapper images resulted in an overall accuracy of 35% (Mumby *et al.*1997) and a classification of macroalgae in an intertidal zone using hyperspectral (13 bands) images resulted in overall accuracy of 86 % (Bajjouk *et al.* 1996). The high accuracy of the macroalgae classification is due to the increased number of bands used (Mumby *et al.*1997, Bajjouk *et al.* 1996). Assessing the accuracy in the present study of each individual class, results for 1–170 mg Chl *a* m^{-2} (accuracy 40 %) and 290+ mg Chl *a* m^{-2} (accuracy 52 %) in comparison with that of the bare substratum (accuracy 34 %; Mumby *et al.* 1997) the present result is higher. The instability of the 171-290 mg Chl *a* m^{-2} class was likely to due to the lack of a normal distribution of observed values.

The common approach to mapping the spatial extend of benthic microalgae involves obtaining large numbers of sediment cores (Heil *et al.* 1998, Light and Beardall 1998). This is an effective, but very cost and labor intensive method that still only results in partial coverage. The fieldwork in particular is an important time factor, in terms of logistics and organization in remote locations and shallow water environments, e.g. coral reefs. Remote sensing is a cost beneficial alternative as it reduces the field sampling.

The importance of benthic microalgae was not identified until recently, hence the delayed application of remote sensing to determine its spatial extent and biomass. Other studies have classified areas with benthic microalgae, but has categorized them as sand, like the shallow lagoon and reef flat zones (Ahmad and Neil 1994, Jupp 1985). The present study showed that these areas consist of different concentrations of benthic microalgae and as established that sediment (sand) is one of the major habitats where benthic microalgae are located (Heil *et al.* 1998, Paterson *et al.* 1998, MacIntyre *et al.* 1996, Miller 1996). The present study also demonstrated that it is possible to distinguish variable concentrations of benthic microalgae in coral reef sediment by comparing their spectral reflectance. A similar study, located at an intertidal temperate mud flat, also established relationships between benthic microalgae and spectral reflectance (Paterson *et al.* 1998).

Interpretation of the classified image will improve when the number of training sites and therefore the number of field sample sites increases, since this influences the inter- and extrapolation within the classification algorithm (Jensen 1996). Further improvements are possible by utilizing hyperspectral remote sensing techniques through improved accuracy of the signature resulting from increase in the number of bands and resolution (Paterson *et al.* 1998, Mumby *et al.* 1997, Jensen 1996.). As a result of the hyperspectral approach there will be an increase in the ability to distinguish small scale patterns and benthic microalgal compositions which were not currently visible in the present classification (Paterson *et al.* 1998, Atkinson and Curran 1997).

Disturbances in the present classified image were due to small scale patterns caused by clouds and spectral mixing of corals, deep water and high benthic microalgal concentrations. Structure and size of sediments (Goetz 1992) can also influence spectral mixing. It is therefore advised to compare the signature of different sediments with and without benthic microalgae, although benthic microalgae was found in all sediment samples in the present study.
To correct for water column effects different training sites for deep and shallow water were determined and this could be improved by addition of bathymetry

data. With bathymetry a model can be applied to reduce the water column effects (Mumby 1997, Bierwirth 1993, Lyzenga 1981). Further improvement could be accomplished by conducting the remote sensing during no or low cloud cover, solar zenith, low tide (Jensen 1996, Mumby *et al.* 1998).

Vertical migration can influence benthic microalgal distribution on short time scales (Heil *et al.* in review, Paterson *et al.* 1998, MacIntyre *et al.* 1996). This therefore means that in a short period (hours) after the remote sensor obtains the image, spatial extent could change and therefore the classified image would change. By analysing repeated images a more comprehensive benthic microalgal distribution map can be established. This is, however, advantageous, as conventional methods are unable to detect wide-scale short-term changes in benthic microalgal biomass (Paterson *et al.* 1998, MacIntyre *et al.* 1996).

Benthic microalgae in temperate areas have been relatively well studied compared to benthic microalgae in tropical, specifically coral reef environments (MacIntyre *et al*. 1996, Miller *et al.* 1996). The relationship between the benthic microalgae and sediment size and structure, vertical migration and productivity measurements (MacIntyre *et al.* 1996) have not had an equivalent effect in coral reef environments.

Future research using remote sensing will improve with an increase in the number of available satellites which will have an increased; resolution, spectral bands, coverage and shorter repeat times and in addition data will be easier accessible (Stoney 1997, Aplin *et al.* 1997). It is predicted 31 new remote sensing satellites will go into orbit by 2000.

The use of remote sensing techniques may standardize different applications (Holden and LeDrew 1998). For instance, the method of determination of the extent of benthic microalgae on Heron Reef could be used on other reefs (e.g. 770 shallow reefs in the Great Barrier Reef) or other periods on the same reef thereby making it a reliable comparison for monitoring purposes.

Conclusions

This research has demonstrated that even with a limited amount of sampling sites, 3 spectral bands and low resolution (30 x 30 m) a signature for benthic microalgal concentrations can be determined and the spatial extent of the benthic microalgae can be estimated using remote sensing. Various advantages and disadvantages of the remote sensing technique have already been demonstrated in other field of marine biology research (Mumby 1998, Chauvaud *et al*. 1998, Holden and LeDrew 1996). The present study can contribute to the refinement of remote sensing techniques, remote sensing can be a powerful research tool for shallow water coral reef environments. The present study further highlighted the potential role that remote sensing can have in determining extent and concentration of benthic microalgae (Paterson *et al.* 1998). Knowledge of the extent of benthic microalgae on Heron Reef makes it possible to relate benthic microalgal concentration to different processes on the reef. Monitoring these processes (e.g. primary production) will improve the understanding of how reef ecosystems behave and are influenced (by natural and anthropogenic activities) and will therefore be important for assessing the ecological health of coral reefs.

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Appendix

Appendix A Error matrix

Appendix B Postgraduate diploma presentation