Can. J. Remote Sensing, Vol. 35, No. 3, pp. 276–286, 2009

Coral health monitoring: linking coral colour and remote sensing techniques

Ian A. Leiper, Ulrike E. Siebeck, N. Justin Marshall, and Stuart R. Phinn

Abstract. Percent of living coral cover is an indicator commonly used to assess reef status. This study tested whether Coral Health Chart scores could be used as a proxy for spectral reflectance, which would provide a basis for mapping living coral cover at a finer scale (colour) using remote sensing techniques. A total of 1264 spectral reflectance measurements were taken in situ from corals representing the colour scores on the Coral Health Chart at Heron Island, Great Barrier Reef, Australia. Spectral analyses of reflectance magnitude showed that living coral could be classified with 72.41% overall accuracy into three colour categories: bleached, medium, and dark coral. First- and second-order derivative analyses did not improve the accuracy of classifying coral spectra into colour categories. Spectral analyses using only coral spectra from the genus *Acropora* also failed to improve classification results significantly, consistent with suggestions that coral reflectance is independent of taxonomy at the genus level. The results of this study provide a foundation for using the Coral Health Chart as a proxy to map and monitor living coral condition using remote sensing techniques.

Résumé. Le taux de couverture corallienne vivante est l'un des indices communément utilisé pour l'évaluation de l'état de santé des récifs. Cette étude vise à déterminer si les catégories définies par le « coral health » chart peuvent être utilisées comme proxy de la reflectance spectrale, ce qui procurerait une base pour la cartographie de la couverture corallienne vivante à fine échelle (couleur) à partir de la télédétection. Un total de 1264 reflectances spectrales a été relevé à Heron Island, Grande Barrière de Corail, Australie, sur des coraux représentatifs des catégories de couleur du « coral health chart ». L'analyse spectrale des magnitudes de reflectances montre que les coraux vivants peuvent être classés selon trois catégories : blanchi, intermédiaire, et sombre, avec une précision globale de 72,41 %. Les analyses par dérivées spectrales de premier et second ordres n'améliorent pas la précision de la classification des spectres coralliens en catégories de couleur. Les analyses spectrales ne portant que sur les spectres coralliens du genre *Acropora* échouent également à améliorer les résultats de manière significative, ce qui est cohérent avec le fait que la reflectance corallienne soit indépendant de la taxonomie au niveau du genre. Les résultats de cette étude apportent une base pour l'utilisation du « coral health chart » comme proxy de la reflectance spectrale pour la cartographie et le suivi de la santé de coraux vivants à partir de la télédétection.

Introduction

Monitoring the health of coral reefs at appropriate temporal and spatial scales is important if we are to maintain these complex and highly productive ecosystems (Bryant et al., 1998; Hoegh-Guldberg et al., 2000). Methods used to monitor coral reef health include video, line, and belt transects (Marshall and Baird, 2000; Pernetta, 1993); manta tows (Miller and Muller, 1999); measuring photosynthetic activity (Fitt et al., 2001); and counting symbiotic dinoflagellates and determining chlorophyll *a* content (Hoegh-Guldberg and Smith, 1989). These methods are confined to specific spatial and temporal scales, and the spatial scales to which they can be applied are not always appropriate, given the extent of mass bleaching events and scales of resource management (Green et al., 2000; Mumby et al., 1999; Roelfsema et al., 2006). Remote sensing is a method that offers the potential to assess reef status over large spatial scales, introducing the possibility of monitoring trends and events, such as coral bleaching, more effectively. A new tool developed as an alternative method to monitor coral reef health that works on a scale in between remote sensing and spot measurements and provides a link between the two is the Coral Health Chart (Siebeck et al., 2006).

Coral Health Charts provide a quick, inexpensive, and noninvasive way to monitor coral condition based on colour (Siebeck et al., 2006). The charts provide an objective measure of coral bleaching, in contrast with many observations that are based on observer perception (Berkelmans and Oliver, 1999; Holden and LeDrew, 1998). As corals bleach, their brightness increases and saturation decreases because of the number of symbiotic dinoflagellates and associated pigments remaining within the coral tissue (Kleppel et al., 1989). Coral Health

---

Received 5 February 2009. Accepted 20 May 2009.
Published on the Web at http://pubservices.nrc-cnrc.ca/rp-ps/journalDetail.jsp?jcode=cjrs&lang=eng on 26 August 2009.

I.A. Leiper[1] and S.R. Phinn. Centre for Remote Sensing and Spatial Information Science, School of Geography, Planning and Environmental Management, The University of Queensland, Brisbane 4072, Queensland, Australia.

U.E. Siebeck and N.J. Marshall. Sensory Neurobiology Group, School of Biomedical Sciences, The University of Queensland, Brisbane 4072, Queensland, Australia.

[1] Corresponding author (e-mail: i.leiper@uq.edu.au).

Charts document this transformation over six colour stages and are sensitive enough to detect naturally occurring fluctuations of symbiont density (Siebeck et al., 2006). Direct comparison of colour score data is viable within and between studies due to the standardised colour chart design, and the condition of a coral colony can be monitored by following the temporal colour score values.

Numerous studies have shown that remote sensing can be used to identify and map reef benthos such as coral, algae, and sand (Hochberg and Atkinson, 2000; Holden and Ledrew, 1999; Joyce and Phinn, 2003; Mumby et al., 1997; 2004; Yamano and Tamura, 2004). Because spectral reflectance signatures of coral reef substrate types have been shown to be relatively invariant between geographic locations, partly due to the common suite of pigments, an opportunity exists to create global classification schemes (Hochberg et al., 2003; Holden and Ledrew, 1999). To gather meaningful data on reef condition or health using remote sensing, a commonly accepted measure of actual reef health needs to be identified (Joyce and Phinn, 2003). Joyce et al. (2004) explored the "reef check" classification scheme with Landsat-7 Enhanced Thematic Mapper Plus (ETM+) image data with limited success, possibly due to the moderate spatial resolution and broad spectral bandwidth of the satellite.

In this study, we attempted to link a different in situ method of assessing reef health, based on the visual assessment of coral colour, with remote sensing techniques. We further developed the monitoring concept introduced by the Coral Watch system (Siebeck et al., 2006; www.coralwatch.org), testing whether Coral Health Chart colour scores could be used as a proxy for spectral reflectance.

Specifically, we tested whether spectral reflectance signatures, taken in situ from corals representing each colour score on the Coral Health Chart, were distinct and separable from one another. If so, we could define classification boundaries to assign a colour score to coral spectral reflectance signatures. This would provide the basis for producing temporal images mapping changes in coral colour score, which would be a valuable tool for monitoring reef health, resilience, and recovery.

Materials and methods

Coral Health Charts

Coral Health Charts (**Figure 1**) provide a quick, inexpensive, and noninvasive way to assess and monitor coral condition based on the colour of corals (Siebeck et al., 2006). The front of the chart shows 24 colour squares sorted into four groups according to hue. For each hue (marked B–E in the chart), six brightness–saturation levels are shown (marked 1–6 in the chart). To take a colour chart measurement, the chart is placed beside a coral and the colour score that is the closest match to the colour of the coral is recorded. Only the number from the colour score is used when analysing Coral Health Chart data, as it relates to the brightness and saturation of coral–algal pigmentation and best describes the colour change as corals lose their symbionts. The letter value, representing hue, is merely to assist observers in identifying which colour square matches best with the coral colour. When there is no direct hue match, the nearest equivalent in the Coral Health Chart is used. In terms of coral condition, the values ranging from 1 to 6 tend to represent a graduation from severely bleached coral to very healthy coral. (However, it is important to note that there are many corals that are perfectly healthy with a colour score of 3 or 4). Colour scores are henceforth abbreviated to "cs" (e.g., a colour score of 1 is given as cs1). The most effective use of the chart is to follow the trend of temporal colour scores to monitor coral condition.

Data collection

Data were collected during March 2005 on the southwestern portion of Heron Reef, Queensland, Australia (23°27′S, 151°55′E). Reflected radiance measurements were taken in situ from corals representing each colour score in the Coral Health Chart. Radiance reflectance measurements across an effective spectral range of 300–800 nm were recorded using an Ocean Optics USB2000 fibre optic spectrometer, with a 25° field of view. Before each measurement, a reference reading of a 99% Lambertian reflectance standard (Spectralon) was taken to represent solar irradiance conditions, along with a dark current reference reading. Reference readings were taken underwater adjacent to the coral target. The sensors were held motionless at an angle orthogonal to the plane of the sun approximately 0.5–1.0 cm from the target. Each spectral measurement was an average of 10 spectra taken using integration times appropriate to the light field.

Coral targets were randomly selected based on their colour score. For each target, a photograph was taken and then the reflectance radiance, colour score, morphology, and genus were recorded. The final dataset contained $n = 1264$ coral spectral reflectance signatures, with at least 100 signatures for each colour score (cs1, $n = 281$; cs2, $n = 378$; cs3, $n = 218$; cs4, $n = 141$; cs5, $n = 128$; cs6, $n = 118$). This dataset was termed the 2005 dataset.

An *Acropora* dataset was also formed to test if classification success was greater when considering only one genus of coral. All *Acropora* spectra from the original dataset were extracted to form an *Acropora* dataset, consisting of 760 spectra (cs1, $n = 230$; cs2, $n = 238$; cs3, $n = 188$; cs4, $n = 69$; cs5, $n = 35$; cs6, $n = 0$).

Spectral reflectance analysis

Coral spectra were initially analysed for discrimination based on magnitude of reflectance values. Reflectance units were calculated from dark current corrected, upwelling radiance measurements from each target and a Spectralon panel ((coral radiance – dark radiance)/(Spectralon panel radiance – dark radiance)). The resulting reflectance spectra were resampled to 1 nm intervals across a spectral range of 400–700 nm, with reflectance units ranging from zero to one.

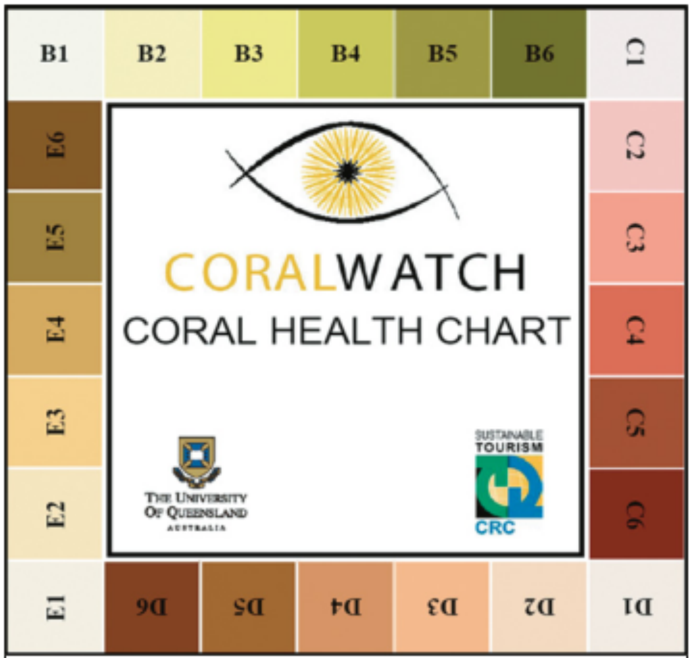


Figure 1. Coral Health Chart. The front of the chart shows 24 different colour scores sorted into four groups according to hue. For each hue (B–E) there are six brightness–saturation levels (1–6) that relate to the amount of symbiont density and chlorophyll *a* content.

The visible-wavelength range matches passive remote sensor frequencies available for coral reef mapping.

There was sufficient replication in the 2005 and *Acropora* datasets to use a proportion of spectra for boundary definition and the remaining spectra to test the model. For the 2005 dataset, the median of 50 randomly selected spectra was plotted from each colour score, and classification boundaries were subsequently defined as the midpoint between two contiguous median reflectance spectra (**Figure 2A**). The number of replicates for each colour score varied dramatically in the *Acropora* dataset. For consistency, we matched the percentage of spectra selected to define boundaries for the 2005 dataset to define boundaries for the *Acropora* dataset. For example, from cs1 in the 2005 dataset, 50 spectra from a total of $n = 281$ were randomly selected to define the cs1/2 classification boundary. Therefore, 18% of spectra (50/281 × 100) were taken from cs1 in the *Acropora* dataset to define the cs1/2 classification boundary.

With the newly defined classification boundaries, the remaining coral spectra from the 2005 and *Acropora* datasets were plotted and assigned a colour score according to which spectral boundaries the curves fell within (each dataset using their respective classification boundaries). Where spectra fell within two or more colour scores (i.e., the spectral curve crossed over a boundary line), the field in which the majority of the spectral curve occurred was selected as the representative colour score for classification. The proportion of spectra whose classified colour score matched the in situ colour score was used to calculate the accuracy of the model (number of correctly classified spectra).

Due to the level of spectral variation within each colour score, some colour scores were then grouped together and the initial classification boundaries revised. Colour scores with the lowest initial classification accuracy, due to high confusion with contiguous colour scores, were grouped together and the boundaries redefined (**Figures 2B–2D**). Data were then reclassified to test if the new boundaries provided more successful discrimination.

Derivative analysis

Analysis of derivative plots has been shown to improve spectral discrimination of corals by amplifying subtle differences in reflectance (Clark et al., 2000; Hochberg et al., 2003; Holden and LeDrew, 1998). First- and second-order derivative plots of the median spectra (**Figure 3**), were calculated using a routine implemented in the IDL/ENVI image-processing package. First derivatives describe the gradient of a spectrum, and second derivatives describe the change in gradient (Clark et al., 2000).

Visual inspection of the derivative plots revealed wavelengths where discrimination between colour scores looked likely. These wavelengths were located where derivative values for colour scores seemed isolated from remaining colour score values (**Figure 3**). At these wavelengths, classification boundaries were defined as the midway value between the selected colour score value and the nearest remaining colour score value. Using these classification boundaries, remaining spectra were assigned a colour score according to their derivative values at the selected wavelengths. Classification accuracy was defined as the percentage of corals whose classified colour score (using derivative boundaries) matched their in situ colour score.

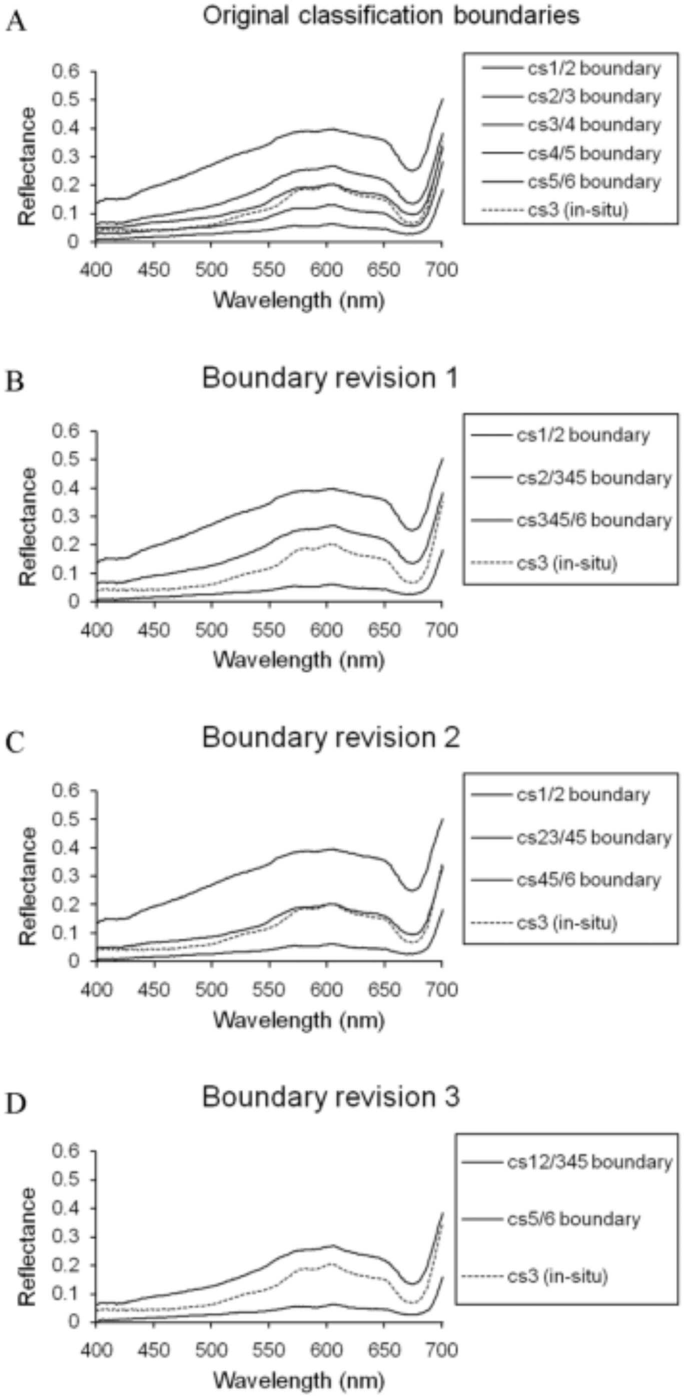
Results

Spectral reflectance analysis

The 2005 dataset

The median spectral reflectance signatures taken from corals representing all six colour scores in the Coral Health Chart and subsequently used to define classification boundaries are shown in **Figure 4A**. As the colour score increased, the magnitude of reflectance decreased. Normalised reflectance curves highlighted the distinct triple-peaked pattern described for brown-mode hermatypic corals (Hochberg et al., 2003; 2004) and its subsequent reduction in prominence as corals bleach and lose symbiotic pigments (Hedley and Mumby, 2002; Hochberg et al., 2003; Mumby et al., 2004) (**Figure 4B**).

A high proportion of spectra were correctly classified for cs1 (77.49%) and cs6 (76.47%) using the original set of classification boundaries (**Figure 2A**). Lower accuracy was recorded for cs2 (44.21%), cs3 (31.55%), cs4 (26.37%), and



Colour score	Correct
1	77.49%
2	44.21%
3	31.55%
4	26.37%
5	41.03%
6	76.47%
Overall accuracy	50.31%

Colour score	Correct
1	77.49%
2	44.21%
345	62.02%
6	76.47%
Overall accuracy	60.68%

Colour score	Correct
1	77.49%
23	66.94%
45	47.34%
6	76.47%
Overall accuracy	66.70%

Colour score	Correct
12	78.18%
345	62.02%
6	76.47%
Overall accuracy	72.41%

Figure 2. Classification boundaries and respective classification success for the 2005 dataset. For each colour score (cs), the median of 50 randomly selected coral spectra was plotted, and classification boundaries were defined as the midpoints between two contiguous median reflectance spectra. An example raw data reflectance signature from coral with an in situ colour score of 3 provides a reference to the changes between boundary classification schemes from (A) original classification boundaries, (B) boundary revision 1, (C) boundary revision 2, and (D) boundary revision 3.

cs5 (41.03%). The total proportion of spectral reflectance signatures correctly classified was 50.31% (**Figure 5A**).

Revising the classification boundaries increased classification success (**Figures 2B–2D**). Combining colour scores 3, 4, and 5 (cs345) resulted in a classification success of 62.02% and an overall success of 60.68% (**Figure 2B**). Combining colour scores 2 and 3 (cs23) and 4 and 5 (cs45) produced classification success of 66.94% and 47.34%, respectively, and an overall success of 66.70% (**Figure 2C**). Refining the classification boundaries to only three colour score groups produced the greatest overall

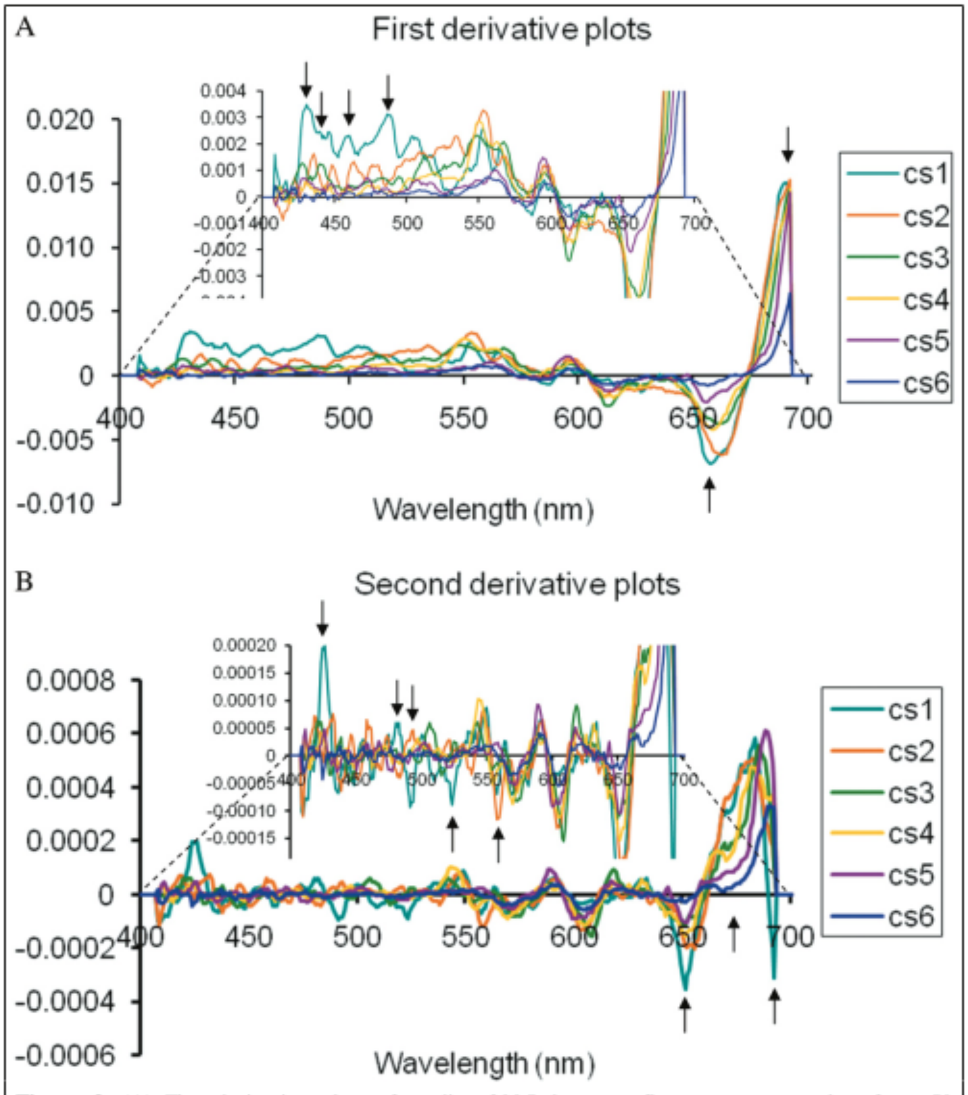


Figure 3. (A) First-derivative plots of median 2005 dataset reflectance curves taken from 50 randomly selected coral reflectance spectra of each colour score. Arrows indicate areas selected for discrimination at 431, 443, 458, 489, 662, and 692 nm. (B) Second-derivative plots of median 2005 dataset reflectance curves taken from 50 randomly selected coral reflectance spectra of each colour score. Arrows indicate areas selected for discrimination at 425, 483, 493, 523, 558, 651, 675, and 692 nm.

classification success (72.41%). Classification success was 78.18%, 62.02%, and 76.47% for cs12, cs345, and cs6, respectively (**Figure 2D**).

Acropora dataset

The median spectral reflectance curves of the *Acropora* dataset, representing colour scores 1–5 in the Coral Health Chart, increased in magnitude of reflectance as the colour score decreased (**Figure 4C**). Like the 2005 dataset, normalised reflectance curves highlighted a distinct triple-peaked pattern described for brown-mode corals (Hochberg et al., 2003; 2004) and its subsequent reduction in prominence as corals bleach and lose symbiotic pigments (Hedley and Mumby, 2002; Hochberg et al., 2003; Mumby et al., 2004) (**Figure 4D**).

With classification boundaries defined between each of the median spectral reflectance curves (as in **Figure 2A** for the 2005 dataset), a high proportion of spectra were correctly classified for cs1 (83.83%) and cs5 (100.00%), and lower proportions were successfully classified for cs2 (43.93%), cs3 (25.00%), and cs4 (29.17%) (**Figure 5B**). The total proportion of spectral reflectance signatures correctly classified was 52.94% (**Figure 5A**). As with the 2005 dataset, boundary revision increased classification success (**Figure 5**). A lack of *Acropora* spectra with an in situ value of cs6 influenced the results, with an increase in classification success of cs5 (**Figure 5B**).

Derivative analysis

The 2005 dataset

Visual inspection of the derivative plots (**Figure 3**) suggested that we would be able to discriminate most of the colour scores based on first-derivative values. The region showing highest differentiation was between 430 and 490 nm. Four wavelengths (431, 443, 458, and 489 nm) were selected in this region to test for discrimination of cs1 spectra from the rest of the colour scores using first-derivative values (**Figure 3A**). Additionally, we attempted to discriminate cs12 from cs34 from cs56 at 662 nm and cs6 from cs12345 at 692 nm.

Despite areas where median derivative curves appeared to be well separated from one another and had a relatively high overall classification accuracy, the specific colour score that was being tested for separation showed only moderate classification accuracy (**Figure 6A**). For example, classification success of cs1 at 431 nm was 64.50%, compared with 83.85% overall success at 431 nm. Using first-derivative values it appeared plausible only to identify severely bleached corals (cs1) at 431, 443, and 458 nm, with moderate success, and the remaining colour scores (cs23456) remained clustered together.

Second-derivative plots of the reflectance spectra revealed eight wavelengths (425, 483, 493, 523, 559, 651, 675, and 692 nm) where at least one colour score was visually separable (**Figure 3B**). At all except two of these wavelengths we tested whether cs1 could be separated from cs23456. The exceptions were at 559 nm, separating cs2 from cs13456, and at 675 nm, separating cs12 from cs34 from cs56.

Second-derivative values were less successful than first-derivative values for discrimination of coral spectra representing corals of different colour scores (**Figure 6B**).

Acropora dataset

Visual inspection of the *Acropora* dataset derivative plots suggested that two colour scores would be separable based on first-derivative values. Three wavelengths (429, 466, and 598 nm) and two wavelengths (553 and 665 nm), respectively, were selected to test for discrimination of cs1 and cs5 coral spectra from the rest of the colour scores.

Extraction of severely bleached corals (cs1) was moderately successful at 429 nm, with 89.37% of corals correctly classified (including 58.60% of cs1 corals). At 665 nm it was possible to extract very healthy corals (cs5) with very high accuracy (100%), with an overall accuracy of 87.41%. This result is likely influenced by a lack of corals representing cs6 in the dataset. No further separation of the remaining *Acropora* coral spectra (cs234) was possible with sufficient accuracy.

Second-derivative plots also revealed numerous wavelengths to test for discrimination of colour scores: separating cs1 from cs2345 at 423, 440, 462, 485, 591, 620 nm; cs12 from cs345 at 478 nm; cs2 from cs1345 at 497, 554, and 563 nm; cs4 from cs1235 at 566 nm; and cs5 from cs1234 at 679 nm. No colour scores were adequately separable using second-derivative values (**Figures 7B, 7C**).

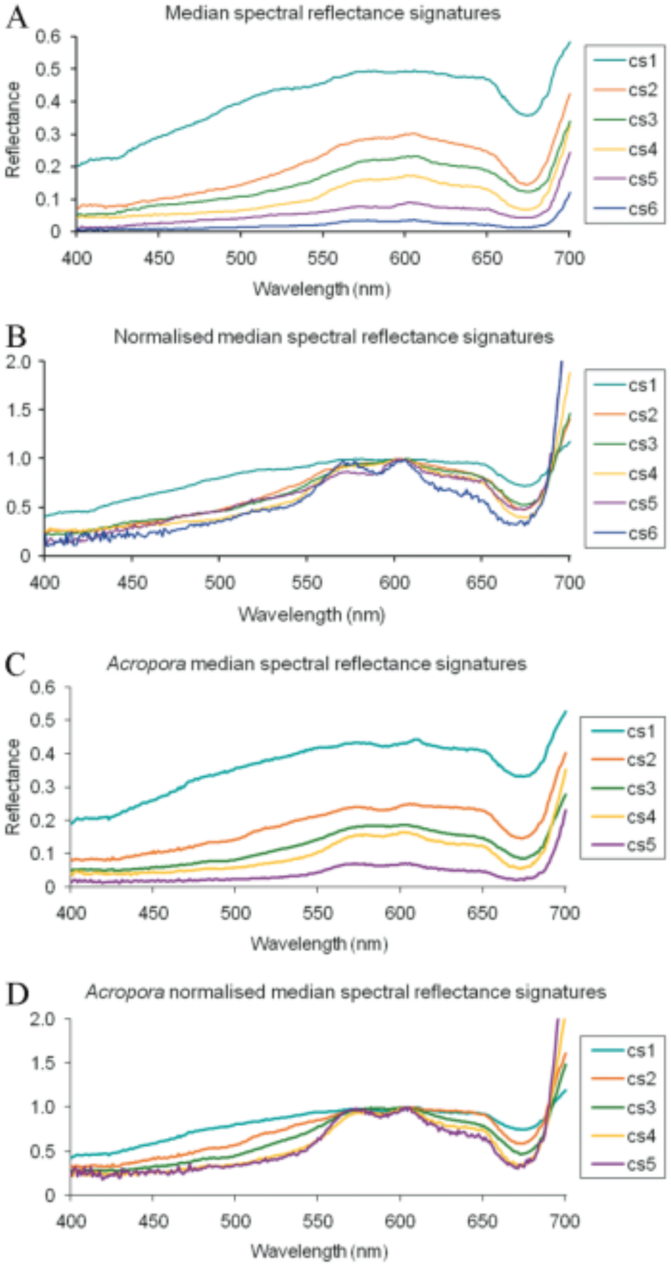


Figure 4. (A) The 2005 dataset median reflectance curves for corals representing the colour scores on the Coral Health Chart. (B) Normalised 2005 dataset median reflectance curves, highlighting spectral shape regardless of reflectance magnitude. Curves were normalised to the maximum reflectance value between 400 and 675 nm. (C) *Acropora* dataset median reflectance curves for corals representing the colour scores on the Coral Health Chart. (D) Normalised *Acropora* dataset median reflectance curves, highlighting spectral shape regardless of reflectance magnitude. Curves were normalised to the maximum reflectance value between 400 and 675 nm.

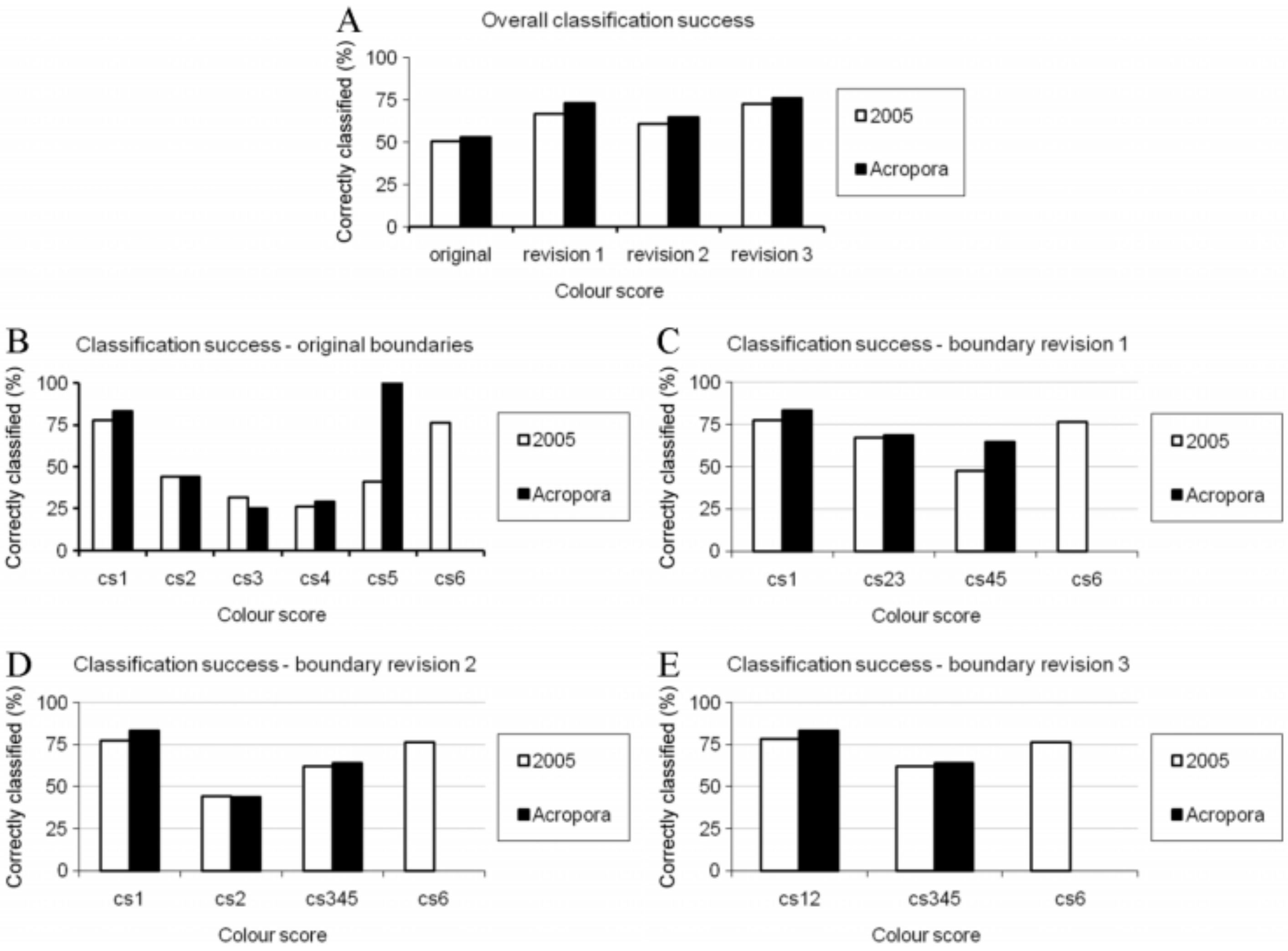


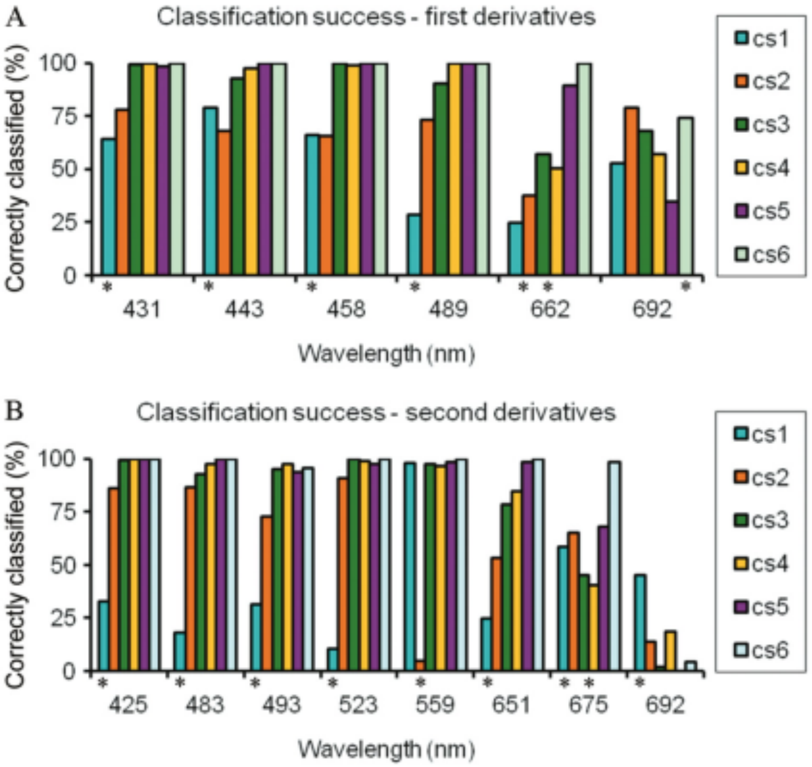
Figure 5. Classification success for magnitude of reflectance tests using the 2005 and *Acropora* datasets: (A) overall classification success; (B–E) classification success using original boundaries, and subsequent boundary revision. Classification accuracy was defined as the percentage of corals whose classified colour score matched their in situ colour score.

Discussion

It is widely accepted that bleached coral has a higher reflectance (in the visible-wavelength range) than healthy coral and that the resulting change in reflectance signal is strong enough to be detected using remote sensing at specific spatial and spectral resolutions (Andrefouet et al., 2002; Elvidge et al., 2004; Holden and LeDrew, 1998; Yamano and Tamura, 2004). Using the Coral Health Chart, this study was able to further explore spectral reflectance dynamics associated with graduations in coral health.

Siebeck et al. (2006) showed that a reduction in symbiont and chlorophyll *a* content as corals bleach was correlated with an increase in brightness and decrease in saturation of coral colour (hue remains relatively constant). Taking into consideration the human visual system and the colour change corals undergo during bleaching, the Coral Watch system has developed the Coral Health Chart that can record coral condition in more detail than the traditional separation of live hermatypic corals into bleached and nonbleached groupings (Hochberg et al., 2003; Holden and LeDrew, 1997). We used the Coral Health Chart in this study to provide an objective standardised method to measure coral health which had previously been lacking in coral health remote sensing research. Previous studies attempting to spectrally identify healthy coral and bleached coral have revealed promising and sometimes extremely high classification success (Hochberg et al., 2003; Holden and LeDrew, 1998), but it is often unclear how researchers selected their coral targets and how this may have influenced their results. As **Figure 4A** shows, it would not be difficult to successfully distinguish cs1 from cs5 or cs6 if they were the only coral targets surveyed.

The spectral reflectance analysis showed that it was possible to assign a colour score to coral spectral reflectance signatures, with relatively good accuracy, based on magnitude of reflectance plots. Severely bleached coral (cs1) and very healthy coral (cs6) were classified with greater than 75% accuracy using all models (**Figures 2A–2D**). Classification



1D Overall accuracy

Wavelength (nm)	Correct
431	83.85%
443	82.82%
458	80.23%
489	72.15%
662	43.75%
692	64.06%

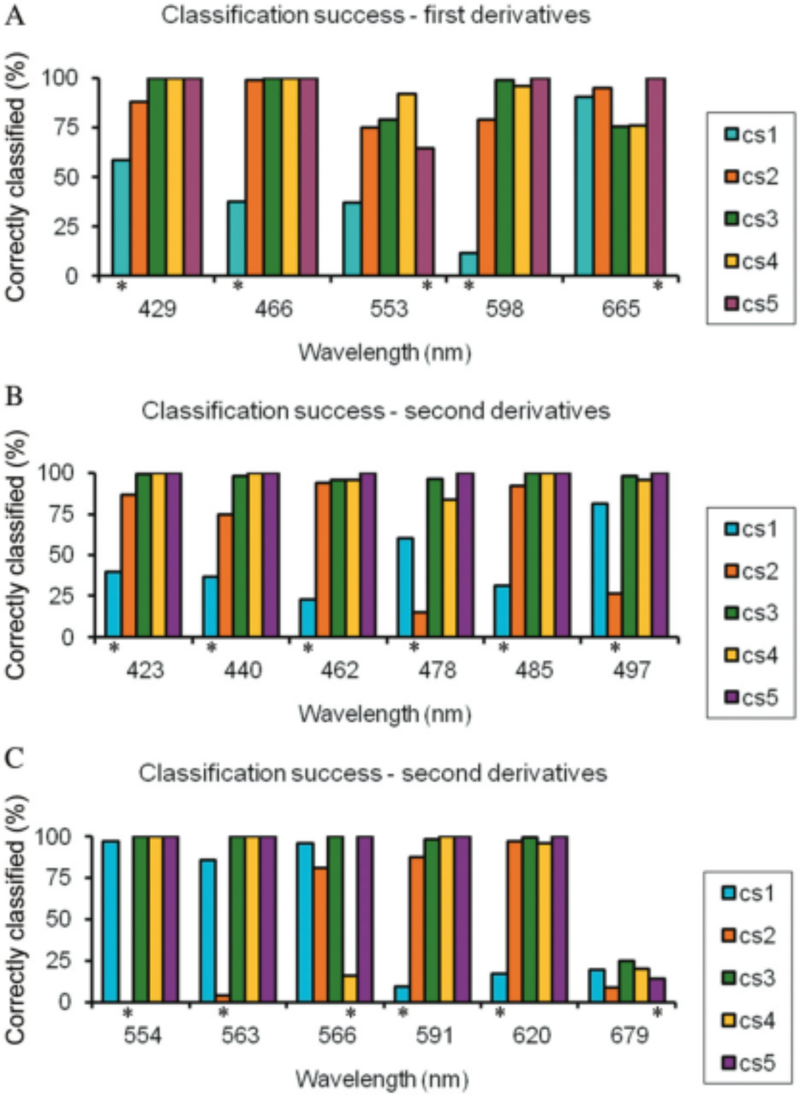
2D Overall accuracy

Wavelength (nm)	Correct
425	79.19%
483	74.43%
493	72.57%
523	75.16%
559	66.46%
651	57.81%
675	57.48%
692	18.97%

Figure 6. (A) First-derivative (1D) and (B) second-derivative (2D) classification results from the 2005 dataset analysis. Classification accuracy was defined as the percentage of corals whose classified colour score matched their in situ colour score. Asterisks denote the colour scores we attempted to discriminate.

accuracy was poor for the remaining four colour scores using the original boundary definition (**Figure 2A**). The Coral Health Chart divides a continuous variable (coral colour) into six bins (cs1–cs6). Therefore, although coral targets were randomly selected using the chart, a plot with six distinct sets of spectral reflectance curves did not occur. The continuity of the variable remained and was evident in the overlapping ranges of spectral reflectance between contiguous colour scores. The variation of spectra around the median curve did not have a normal distribution, and for this reason lower levels of classification accuracy were achieved for cs2, cs3, cs4, and cs5 (cs1 and cs6 each had only one neighbouring colour score into which its spectra may "overlap" and be misclassified). An improvement in classification accuracy was achieved when the number of classification groups was reduced, allowing more room for the variation within each colour score (those that were combined) to be negated. When coral spectra were grouped into three classes, namely bleached (cs12), medium (cs345), and dark (cs6), an overall accuracy of 72.41% was achieved (**Figure 2D**). The reduction from six classes to three, needed for sufficient accuracy, is a limitation of the system for remote sensing and not of the Coral Health Chart. Enriquez et al. (2005) also suggested a limited ability of reflectance-based remote sensors for early detection of coral bleaching after their results showed that the light-harvesting capacity of *Porites branneri* decreased abruptly only for chlorophyll *a* densities below 20 mg·m^{-2} and that absorption spectra taken from corals with a 30-fold variation in chlorophyll *a* density displayed only a five-fold variation in coral absorption.

Derivative plots have been shown to improve identification accuracy of corals by amplifying subtle differences in spectral reflectance (Clark et al., 2000; Hochberg et al., 2003; Holden and LeDrew, 1998). However, derivative analysis findings are too often not consistent between studies, and some papers have published contradicting results (Hedley and Mumby, 2002; Karpouzli et al., 2004). Our derivative findings were not encouraging for the classification of coral spectra into numerous health graduations. Despite areas where median derivative curves appeared to be well separated from one another (**Figure 3**), assigning colour scores to coral spectral reflectance signatures based on derivative values was not very successful. Using first-derivative values it was possible to extract severely bleached corals (cs1) with relatively high accuracy, but it was not possible to separate the remaining coral spectra (cs23456) with sufficient accuracy. Using second-derivative values proved even less successful for discrimination, with 45.02% the highest accuracy achieved when separating severely bleached corals (cs1). Refining the colour scores (e.g., combining cs12, cs34, and cs56) could have produced higher classification success, but with initial derivative separation significantly lower than separation using magnitude of reflectance tests, this avenue was not explored. To combine and average such differently shaped curves (**Figure 3**) was not justified.



1D Overall accuracy

Wavelength (nm)	Correct
429	89.37%
466	87.33%
553	69.47%
598	77.07%
665	87.41%

2D Overall accuracy

Wavelength (nm)	Correct
423	85.14%
440	81.98%
462	81.81%
478	71.21%
485	84.67%
497	80.37%
554	79.46%
563	77.88%
566	78.52%
591	79.05%
620	81.88%
679	17.53%

Figure 7. (A) First-derivative and (B, C) second-derivative analysis results from the *Acropora* dataset. Classification success was defined as the percentage of corals whose classified colour score (using derivative boundaries) matched their in situ colour score. Asterisks denote the colour scores we attempted to discriminate.

Derivative analysis can be useful in separating benthic classes with distinct spectral shapes and may prove useful for taxonomic discrimination when more is understood about coral pigmentation (particularly coral host pigments). At the moment, however, it seems from our dataset that only severely bleached coral (cs1) can be identified from coral spectral shape (derivative) analysis with sufficient accuracy. Our derivative results highlight the importance of carrying out classification analysis. Based purely on a visual assessment of the derivative curves we would have expected very high separability of numerous colour scores, which was not the case. Apart from the range of hues commonly associated with blue-mode, brown-mode, and perhaps green-mode corals (Hochberg et al., 2004; Kutser and Jupp, 2006), very little information can currently be inferred from coral spectral shape. That there were very few corals with a blue-mode reflectance signature in our dataset can be explained by the hues featured in the Coral Health Chart which commonly belong in the green- and brown-mode categories (Hochberg et al., 2004; Kutser and Jupp, 2006).

Hochberg et al. (2003) showed from normalised reflectance data that brown-mode hermatypic coral taken from numerous geographic regions has a very consistent spectral shape. The literature on coral spectra supports this view, with normalised spectral plots showing very similar spectral shapes (Hochberg et al., 2003; 2004). This can explain the poor discrimination between colour scores when using derivatives, a method designed to highlight differences in the shape of spectral curves. When considering **Figure 4B**, it seems logical that shape analysis will have trouble distinguishing more than cs1 from cs23456. Although there are visual differences in gradient (that first-derivative values highlight) between the curves, they are not remarkably different from one another, especially when consideration is given to the variation surrounding each of these median curves. The differences in location of maxima–minima (that second-derivative values highlight) are even less significant, which is not surprising considering that brown-mode corals contain a common suite of pigments (Hochberg et al., 2003). Magnitude of reflectance models were able to separate the colour scores with greater success because this is what changes the most rather than the shape of the curve; the corals still have the same pigments absorbing at the same wavelengths, and it is merely the degree of absorption that changes. Indeed, the position and occurrence of coral spectral peaks are so consistent that corals are often notated according to two modes (brown and blue) (Hochberg et al., 2004). The triple-peaked pattern typical of brown-mode corals became less evident as the colour score decreased, highlighting and supporting the postulation that zooxanthellae pigment absorption primarily determines brown-mode reflectance (Hochberg et al., 2003; 2004). From an operational remote sensing perspective, using magnitude of reflectance values to classify spectra is beneficial in that hyperspectral sensors (a requirement for derivative calculations) are not needed and different parts of the visible spectrum (400–700 nm) could be utilised depending on environmental conditions.

Spectral analysis using only coral spectra from the genus *Acropora* (genus was the lowest taxonomic level recorded during spectral collection) failed to improve classification results significantly. The similarity in classification levels between the 2005 and genus *Acropora* datasets (**Figure 5**) is consistent with suggestions that coral reflectance is independent of taxonomy at the genus level (Hochberg et al., 2004; Kutser and Jupp, 2006).

This study showed that living coral could be further classified into additional categories, including bleached, medium, and dark coloured coral, with relatively high accuracy (72.41%). The study also revealed that Coral Health Charts could be used as a proxy for spectral reflectance when mapping coral condition. Future work should build upon the findings presented in this paper showing that remote sensing can be used to categorise living coral into three condition classes to assess the possibility of mapping coral condition.

Acknowledgements

Sincere thanks to Alan Goldizen, Kylie Greig, and staff at Heron Island Research Station for help and advice during this study. We are grateful to Julie Scopélitis for the abstract translation and an anonymous reviewer for constructive comments. This project was supported by the Australian Research Council, Deep OceanQuest, the University of Queensland Vice Chancellor's Strategic Initiatives and Asian Office of Aerospace Research & Development, and the Centre for Remote Sensing and Spatial Information Science.

References

Andrefouet, S., Berkelmans, R., Odriozola, L., Done, T., Oliver, J., and Muller-Karger, F. 2002. Choosing the appropriate spatial resolution for monitoring coral bleaching events using remote sensing. *Coral Reefs*, Vol. 21, No. 2, pp. 147–154.

Berkelmans, R., and Oliver, J.K. 1999. Large-scale bleaching of corals on the Great Barrier Reef. *Coral Reefs*, Vol. 18, No. 1, pp. 55–60.

Bryant, D., Burke, L., McManus, J., and Spalding, M. 1998. *Reefs at risk: A map-based indicator of threats to the world's coral reefs*. World Resources Institute, Washington, D.C. pp. 56 pp.

Clark, C.D., Mumby, P.J., Chisholm, J.R.M., Jaubert, J., and Andrefouet, S. 2000. Spectral discrimination of coral mortality states following a severe bleaching event. *International Journal of Remote Sensing*, Vol. 21, No. 11, pp. 2321–2327.

Elvidge, C.D., Dietz, J.B., Berkelmans, R., Andrefouet, S., Skirving, W., Strong, A.E., and Tuttle, B.T. 2004. Satellite observation of Keppel Islands (Great Barrier Reef) 2002 coral bleaching using IKONOS data. *Coral Reefs*, Vol. 23, No. 1, pp. 123–132.

Enriquez, S., Mendez, E.R., and Iglesias-Prieto, R. 2005. Multiple scattering on coral skeletons enhances light absorption by symbiotic algae. *Limnology and Oceanography*, Vol. 50, No. 4, pp. 1025–1032.

Fitt, W.K., Brown, B.E., Warner, M.E., and Dunne, R.P. 2001. Coral bleaching: interpretation of thermal tolerance limits and thermal thresholds in tropical corals. *Coral Reefs*, Vol. 20, No. 1, pp. 51–65.

Green, E.P., Mumby, P.J., Edwards, A.J., and Clark, C.D. 2000. *Remote sensing handbook for tropical coastal management*. UNESCO, Paris.

Hedley, J.D., and Mumby, P.J. 2002. Biological and remote sensing perspectives of pigmentation in coral reef organisms. *Advances in Marine Biology*, Vol. 43, pp. 277–317.

Hochberg, E.J., and Atkinson, M.J. 2000. Spectral discrimination of coral reef benthic communities. *Coral Reefs*, Vol. 19, No. 2, pp. 164–171.

Hochberg, E.J., Atkinson, M.J., and Andrefouet, S. 2003. Spectral reflectance of coral reef bottom-types worldwide and implications for coral reef remote sensing. *Remote Sensing of Environment*, Vol. 85, No. 2, pp. 159–173.

Hochberg, E.J., Atkinson, M.J., Apprill, A., and Andrefouet, S. 2004. Spectral reflectance of coral. *Coral Reefs*, Vol. 23, No. 1, pp. 84–95.

Hoegh-Guldberg, O., and Smith, G.J. 1989. The effect of sudden changes in temperature, light and salinity on the population density and export of zooxanthellae from the reef corals *Stylophora pistillata* Esper and *Seriatopora hystrix* Dana. *Journal of Experimental Marine Biology and Ecology*, Vol. 129, No. 3, pp. 279–303.

Hoegh-Guldberg, O., Hoegh-Guldberg, H., Stout, D.K., Cesar, H., and Timmerman, A. 2000. *Pacific in peril: biological, economic and social impacts of climate change on Pacific coral reefs*. Greenpeace International, Amsterdam. Greenpeace Report GR249. 72 pp.

Holden, H., and LeDrew, E. 1997. Spectral identification of coral biological vigour. In *IGARSS'97, Proceedings of the International Geoscience and Remote Sensing Symposium*, 3–8 August 1997, Singapore. IEEE, New York.

Holden, H., and LeDrew, E. 1998. Spectral discrimination of healthy and non-healthy corals based on cluster analysis, principal components analysis, and derivative spectroscopy. *Remote Sensing of Environment*, Vol. 65, No. 2, pp. 217–224.

Holden, H., and Ledrew, E. 1999. Hyperspectral identification of coral reef features. *International Journal of Remote Sensing*, Vol. 20, No. 13, pp. 2545–2563.

Joyce, K.E., and Phinn, S.R. 2003. Hyperspectral analysis of chlorophyll content and photosynthetic capacity of coral reef substrates. *Limnology and Oceanography*, Vol. 48, No. 1, pp. 489–496.

Joyce, K.E., Phinn, S.R., Roelfsema, C.M., Neil, D.T., and Dennison, W.C. 2004. Combining Landsat ETM plus and Reef Check classifications for mapping coral reefs: A critical assessment from the southern Great Barrier Reef, Australia. *Coral Reefs*, Vol. 23, No. 1, pp. 21–25.

Karpouzli, E., Malthus, T.J., and Place, C.J. 2004. Hyperspectral discrimination of coral reef benthic communities in the western Caribbean. *Coral Reefs*, Vol. 23, No. 1, pp. 141–151.

Kleppel, G.S., Dodge, R.E., and Reese, C.J. 1989. Changes in pigmentation associated with the bleaching of stony corals. *Limnology and Oceanography*, Vol. 34, No. 7, pp. 1331–1335.

Kutser, T., and Jupp, D.L.B. 2006. On the possibility of mapping living corals to the species level based on their optical signatures. *Estuarine Coastal and Shelf Science*, Vol. 69, No. 3–4, pp. 607–614.

Marshall, P.A., and Baird, A.H. 2000. Bleaching of corals on the Great Barrier Reef: differential susceptibilities among taxa. *Coral Reefs*, Vol. 19, No. 2, pp. 155–163.

Miller, I., and Muller, R. 1999. Validity and reproducibility of benthic cover estimates made during broadscale surveys of coral reefs by manta tow. *Coral Reefs*, Vol. 18, No. 4, pp. 353–356.

Mumby, P.J., Green, E.P., Edwards, A.J., and Clark, C.D. 1997. Coral reef habitat-mapping: how much detail can remote sensing provide? *Marine Biology*, Vol. 130, No. 2, pp. 193–202.

Mumby, P.J., Green, E.P., Edwards, A.J., and Clark, C.D. 1999. The cost-effectiveness of remote sensing for tropical coastal resources assessment and management. *Journal of Environmental Management*, Vol. 55, No. 3, pp. 157–166.

Mumby, P.J., Hedley, J.D., Chisholm, J.R.M., Clark, C.D., Ripley, H., and Jaubert, J. 2004. The cover of living and dead corals from airborne remote sensing. *Coral Reefs*, Vol. 23, No. 2, pp. 171–183.

Pernetta, J.C. (*Editor*). 1993. *Monitoring coral reefs for global change*. IUCN the World Conservation Union, Gland, Switzerland.

Roelfsema, C.M., Phinn, S.R., and Joyce, K.E. 2006. Evaluating benthic survey techniques for validating maps of coral reefs derived from remotely sensed images. In *Proceedings of the 10th International Coral Reef Symposium*, 28 June – 2 July 2004, Okinawa, Japan. Edited by Y. Suzuki, T. Nakamori, M. Hidaka, H. Kayanne, B.E. Casareto, K. Nadaoka, Y. Yamano, and M. Tsuchiya. Japanese Coral Reef Society, Tokyo. pp. 1771–1780.

Siebeck, U.E., Marshall, N.J., Kluter, A., and Hoegh-Guldberg, O. 2006. Fine scale monitoring of coral bleaching using a colour reference card. *Coral Reefs*, Vol. 25, No. 3, pp. 453–460.

Yamano, H., and Tamura, M. 2004. Detection limits of coral reef bleaching by satellite remote sensing: simulation and data analysis. *Remote Sensing of Environment*, Vol. 90, No. 1, pp. 86–103.