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Combining Landsat ETM+ and Reef Check classifications for mapping coral reefs: a critical assessment from the southern Great Barrier Reef, Australia

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Introduction

While the remote-sensing community attempts to find measures of reef "health" able to be detected and mapped using satellite image data, internationally recognized field assessments are already in place to document benthic cover, among other parameters, as an indicator of coral reef status. Reef Check is one such program, designed in 1996 as a globally applicable, rapid, field-survey protocol for coral reef health monitoring by volunteer divers (Hodgson 1999). The protocol is designed to provide a measure of reef health based on indicator species or families for fish, invertebrates, and substrates. Data collected contribute to a global-scale database on coral reef status for use in management plans (Hodgson 1999). Today, over 5,000 trained volunteer divers are led by more than 160 scientists in surveys of 1,500 reefs in 60 countries. During the survey, they record substrate type directly under a measuring tape at 0.5-m intervals on 4×20 m consecutive transects between 3- and 10-m depth (Hodgson and Liebler 2002). The Reef Check substrate classification scheme provides information on benthic habitats such as hard coral, dead coral, soft coral, fleshy algae, rock, rubble, sand, silt, sponge, and other. This is the same type of information that remote-sensing scientists are often asked to extract from image data by coral reef scientists and managers.

Reef Check programs are an important source of reef-health information, yet the data collected will always be point based, and extrapolation to non-surveyed areas will be required. Remotely sensed data can provide a spatially extensive survey if methods are developed to successfully link ground-survey observations, like those provided by Reef Check, with satellite or airborne images. Thus, the objectives of our project were (1) to determine whether Reef Check substrate classes could be successfully mapped with Landsat ETM+ (Enhanced Thematic Mapper Plus) image data, and (2) to determine whether Reef Check data that are currently collected globally may be used for training and assessing the accuracy of remotely sensed image classifications. We address our objectives using a case study in the Capricorn Bunker Group, southern Great Barrier Reef, Australia.

Methods

The Capricorn Bunker Group was selected for ease of access to research stations on Heron and One Tree Islands and to build on past research on Heron Reef (Ahmad and Neil 1994). A rapid, boat-based transect method was used to characterize as many reefs and habitats as possible. Transects were designed to traverse geomorphic zones (Ahmad and Neil 1994), and varied in length from 300 m to 4.5 km. A sampling interval of 50 m between survey points was selected based on logistics and the spatial scale of geomorphic zones on Heron Reef defined from digital aerial photography acquired in October 1999. At each sampling point, two photos were taken simultaneously either side of the boat using underwater digital video cameras. A Global Positioning System recorded the coordinates for each survey point. Transects were concluded when the depth or water quality prohibited confident differentiation between substrate types. A total of 760 survey points were recorded over ten reefs.

A 12-point grid was placed over each photo and the feature below each point recorded and used to calculate percent substrate composition. K-means clustering was then used to identify groups of sites (photos) with similar substrate composition and then assign each photo to a category based on the Reef Check substrate classification system (Hodgson and Liebler 2002). The classes include

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Table 1 Results of K-means clustering of substrate cover in each survey photo showing the average substrate composition in each cluster. Clusters were named according to the dominant substrate in the cluster

Assigned cluster	Area covered (m^2)	Substrate component (%)				
		Sand	Coral	Rock	Rubble	Fleshy algae
Sand	1,019	80	2	1	8	6
Coral	494	7	71	9	9	1
Rock	64	5	5	70	9	6
Rubble	180	17	5	5	67	6
Fleshy algae	51	13	2	6	7	22

live coral (hard and soft), fleshy algae, rubble (0.5–15 cm diameter), rock (including dead coral), and sand/silt (Table 1). Because the water depth (i.e., distance to substrate) and camera's field of view were known, this allowed us to calculate the area covered by individual photos. This ranged between 1–2 m^2 for areas in the lagoons (1–2 m depth) to more than 50 m^2 in water depths greater than 9 m.

Two Landsat 7 ETM+ scenes on successive overpasses on parallel paths were required to cover the Capricorn Bunker reefs (18 and 27 May 2001; path/row 91/76 and 90/76, respectively). Conversion from digital numbers to at-sensor radiance was performed using the gain and offset values provided with the image data. At-sensor reflectance values were also calculated using exoatmospheric irradiance values in each band and the Landsat calibration equations (Landsat Data Users Handbook, 2002). The image data were registered to each other using a first-order polynomial and nearest-neighbor re-sampling to preserve pixel values. Dark pixel subtraction was performed using the average values of deep-water pixels to account for additive atmospheric effects. Each band in the eastern image was normalized to the western image using an empirical line calibration approach; the invariant targets used for the registration process were sand and deep water. Deep oceanic water areas and breaking waves apparent on the reef crests were then masked out and the images were mosaiced using an overlay function with histogram matching.

Several transformed image layers were combined to produce a multi-layer image (blue; green; red; NIR; depth-corrected blue-green, green-red, blue-red; principal components 1, 2, and 3; band ratios blue/green, green/red, blue/red; pan-sharpened blue, green, and red; panchromatic) (Joyce et al. 2002). From this image, several areas considered to be relatively homogenous in cover for each of the Reef Check substrate classes were located and their pixel reflectance values extracted. Image variance and divergence statistics for these sites were assessed to determine which of the original and derived bands provided maximum variance between classes while minimizing within-class variance. These criteria provided the standard optimization factors for image processing. Only a selection of bands met these criteria, significantly reducing the number of layers suitable for use in the classification (i.e., blue, green, red, PCA1, PCA2, PCA3). An unsupervised ISODATA classification was then performed in ERDAS Imagine 8.4 and classes were grouped, split, and named according to field experience.

A refinement to the classification process was required since several of the Capricorn Bunker reefs have lagoons containing pixel (30x30 m) to subpixel scale features that were unable to be detected in the first general classification; there was difficulty in separating individual patch reefs (bommies) from sand in these areas. Thus, the lagoons were extracted from the first classification and classified separately. Since the primary difference between the patch reef

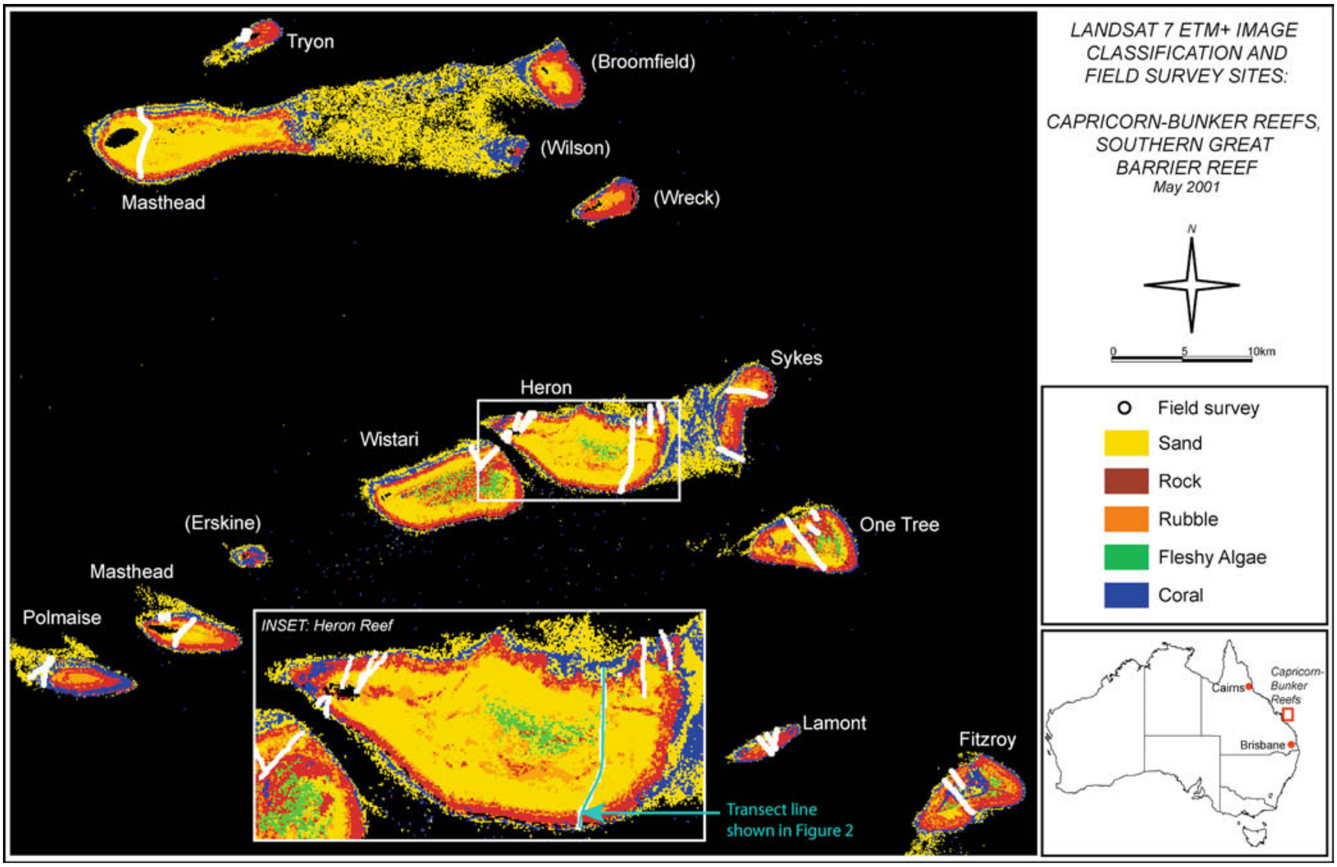

Fig. 1 Output classified image map in the Reef Check classes of the Capricorn-Bunker Group, southern Great Barrier Reef, from Landsat 7 Enhanced Thematic Mapper Plus (ETM+) data collected on 18 and 27 May 2001. Field-survey transects are shown in *white* across the classified reefs

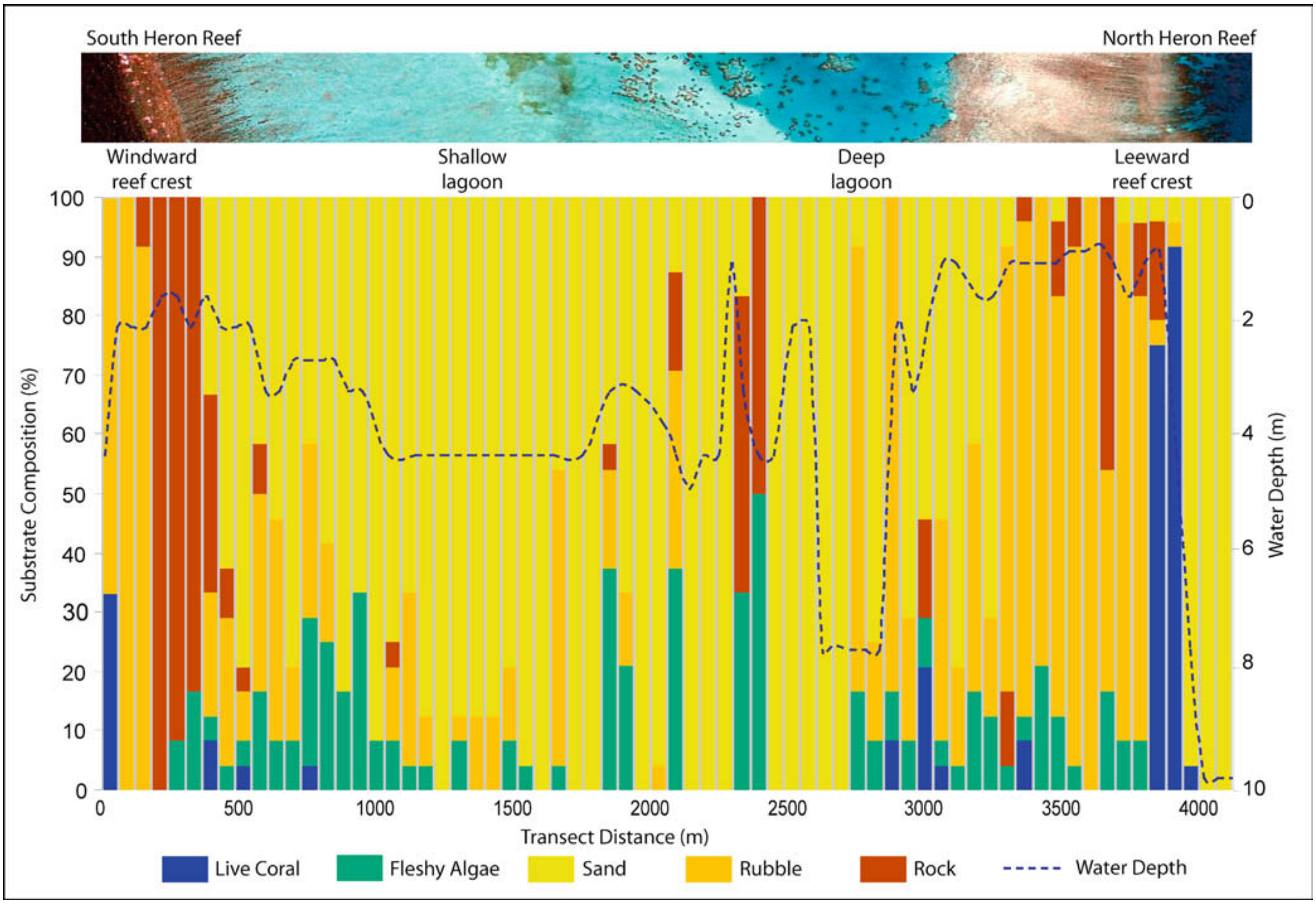

Fig. 2 Transect cross section of Heron Reef showing percent substrate coverage in Reef Check classes determined from field survey data, where 0 m is the southernmost point of the transect line crossing Heron Reef. Water depth at the time of survey is also shown. A 4-m resolution IKONOS image subset at the top shows the spatial patterns of substrate features as seen in high resolution satellite imagery

pixels and sand pixels was a higher red and lower blue value for the bommies, a difference algorithm was applied as:

$$\text{Patch reef separation band} = \left(B_3^2/\sqrt{B_1}\right)*1000$$

where B_3 and B_1 are the reflectance values in Landsat's red and blue band, respectively.

This enhancement was developed based on field experience in the Heron Reef lagoon and supported by higher resolution airborne digital data. An accuracy assessment was conducted by comparing the image class assignment with the field cluster allocation at each survey point.

Results and discussion

The image classification depicts the following classes based on the Reef Check classification scheme: sand, live coral, rock, rubble, and fleshy algae. Rock and rubble may or may not be covered by turf or coralline algae. The remainder of the classes (dead coral, soft coral, sponge, and other) do not appear in the image classification because they did not occur in proportions large enough to comprise the majority substrate at the scale of a Landsat 7 ETM+ pixel. Heron Reef will be used throughout the results and discussion as an example to demonstrate the data collected and analyzed for each reef transect. Figure 1 shows the substrate classification for all reefs, with a more detailed enlargement of Heron Reef. The transect locations can also be seen on individual reefs. The longest transect, which traverses Heron Reef from south to north, is highlighted and the variations in cover shown in Fig. 2. The water depth at the time of data collection (not corrected for tidal variation) is plotted over the substrate composition determined from field data at each survey point along the 4-km transect (Fig. 2). Large areas of rock and rubble are seen towards the reef crest, while the shallow and deep lagoon are dominated by sandy substrates. Fleshy algae was recorded in small portions along most of the transect.

The image-processing procedure applied during this study resulted in a large degree of variance in classification accuracies between reefs (Fig. 3). The overall accuracy of the classification for all reefs combined is considered low (41%); however, the variance about this is strongly affected by individual reef accuracies. Northwest (74%) and Heron Reefs (54%) have noticeably higher individual classification accuracies than all other reefs, in particular Polmaise (12%) and One Tree (15%).

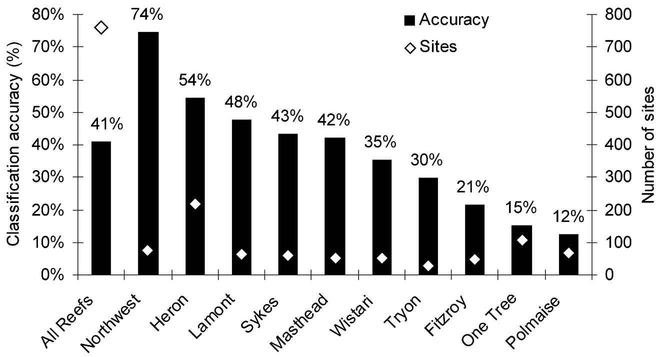

Fig. 3 Overall classification accuracies (%) and number of survey sites per reef based on comparison of field survey data from April 2001 to classified Landsat ETM+ image data (Fig. 1)

Previous classifications of the Capricorn-Bunker reefs do not provide accuracy assessments for comparison (Ahmad and Neil 1994). For the western portion of Heron Reef only, Andréfouët et al. (2003) reported accuracy values between 61 and 66% for the five classes of fore-reef, corals, hard bottom, heterogeneous on soft bottom, and sand. The accuracy was greater when using IKONOS imagery for these same classes (78%). Other reefs classified by Andréfouët et al. (2003) only reached 50–56% with between five and ten habitat classes when using ETM+. The accuracy obtained for individual classes on Heron Reef is documented in Table 2. Both sandy and coral-dominated areas were classified 72% of the time, whereas rock and rubble may be confused with each other. This is not surprising given the scale of the ETM+ image pixel, and indicates a mismatch between the scale of Reef Check classifications and those derived from these image data. Fleshy algae was not documented in the field-survey data, but was classified in the image. This may have been confused with rock because this is still expected to be the underlying substrate and both are spectrally dark targets.

It is possible that the large variations in classification accuracy between reefs may be due to basing the classification on knowledge obtained from all reefs, rather than tailoring the classification to individuals. Highest accuracy figures were achieved in this study for those classes and reef areas that are relatively homogenous over large areas (e.g., Northwest Reef). Considering this particular group of reefs, the large homogeneous areas tend to be dominated by sand or rocky substrates. More heterogeneous reefs with proportionally higher coral or algae (e.g., Tyron and Polmaise Reefs) or those with varying water depth and quality due to extensive or enclosed lagoons (e.g., Fitzroy and One Tree Reefs) tended to be represented at the lower end of the accuracy scale in this classification. Distinctive patterns of substrate assemblages in the Great Barrier Reef are associated with several different reef evolutionary or growth stages (Hopley 1982). Results from Neil et al. (2000) indicated that reefs at similar growth stages exhibited similar relative extents of substrate composition, hence future work should examine if growth-stage stratification within the remotely sensed images enables more accurate classifications.

Ground validation of moderate spatial resolution and broad spectral bandwidth image data such as Landsat ETM+ is not a simple process. In a heterogeneous reef environment, it is particularly difficult to determine the dominant substrate class within a "pixel-sized" area. In this study, we determined the substrate composition every 50 m along a transect, thus assuming that the information acquired in each location, typically covering an area of up to 10 m^2 (though larger in deeper waters), was representative of its surrounds. However, the low accuracy levels for all reefs would suggest that the field validation methods did not adequately characterize substrate categories at the Landsat ETM+ pixel scale.

This study mapped the Reef Check substrate types to accuracies ranging from 12 to 74%, for individual reefs and 40.9% for all reefs combined. The results obtained demonstrate that Landsat ETM+ data can be used to produce maps of reef substrate for several reefs (though the accuracy achieved for others is too poor to conclude positively in general) using an internationally accepted classification scheme; however, significant work is still required to define an optimal field-validation method to match the sampling resolution of the ETM+ image. Here, we suggest that Reef Check substrate data could be beneficial for validating maps of reef substrate types derived from satellite images. Substrate-type maps for coral reefs derived from satellite image data may also contribute to the Reef Check Program by guiding selection of suitable sampling sites and providing a more

Table 2 Error matrix representing reference (field observations) and classified (image-derived) data for Heron Reef. Non-diagonal row totals represent erroneously included pixels (commission errors); non-diagonal column totals represent erroneously excluded pixels (omission errors)

Classified data	Area (km^2)	Reference data: pixels and percentage									
		Sand		Coral		Rock		Rubble		Fleshy algae	
Unclassified		7	44%	6	38%	1	6%	2	13%	0	0%
Sand	20.9	**75**	**72%**	15	14%	3	3%	5	15%	6	6%
Coral	3.6	1	4%	**18**	**72%**	2	8%	4	16%	0	0%
Rock	6.0	4	10%	4	10%	**14**	**35%**	13	33%	5	13%
Rubble	5.3	15	47%	0	0%	3	9%	**11**	**34%**	3	9%
Fleshy algae	1.0	0	0%	0	0%	0	0%	0	0%	**0**	**0%**

spatially extensive coverage of reefs than is possible from diver survey lines. However, some Reef Check classes will not be able to be detected using this approach (e.g., sponges) due to their small size in relation to a satellite image pixel, except if using higher resolution imagery. To increase the value of the Reef Check data for validating substrate maps derived from global archives of moderate spatial resolution image data sets (e.g., Landsat), we recommend increasing the number of sample sites in (1) representative areas of reefs identified from the images and (2) at depths < 10 m. In addition we support maintaining data quality by providing appropriate training, testing, feedback, and guidance to volunteers (Mumby et al. 1995). We also believe it would be appropriate and useful for more generalized, broader habitat descriptions to be recorded en route to the dive sites.

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References

Ahmad W, Neil DT (1994) An evaluation of Landsat Thematic Mapper (TM) digital data for discriminating coral reef zonation: Heron Reef (GBR). Int J Remote Sensing 15(13):2583–2597

Andréfouët S, Kramer P, Torres-Pulliza D, Joyce KE, Hochberg EJ, Garza-Perez R, Mumby PJ, Riegl B, Yamano H, White WH, Zubia M, Brock J, Phinn SR, Naseer A, Hatcher BG, Muller-Karger FE (2003) Multi-sites evaluation of IKONOS data for classification of tropical coral reef environments. Remote Sensing Environ (in press)

Hodgson G (1999) A global assessment of human effects on coral reefs. Mar Pollut Bull 38(5):345–355

Hodgson GA, Liebler J (2002) The global coral reef crisis: trends and solutions. Reef Check

Hopley D (1982) The geomorphology of the Great Barrier Reef: Quaternary development of coral reefs. Wiley, Brisbane

Joyce KE, Phinn SR, Roelfsema C, Neil DT, Dennison WC (2002) Mapping the southern Great Barrier Reef using Landsat ETM and the Reef Check classification scheme. 11th Australasian Remote Sensing and Photogrammetry Conference, Brisbane. CD Rom Proceedings, Causal Productions

Mumby PJ, Harborne AR, Raines PS, Ridley JM (1995) Critical-assessment of data derived from Coral Cay Conservation volunteers. Bull Mar Sci 56(3):737–751

Neil DT, Phinn SR, Ahmad W (2000) Reef zonation and cover mapping with Landsat thematic mapper data: intra- and inter-reef patterns in the southern Great Barrier Reef region. IEEE International Geoscience and Remote Sensing Symposium 2000, Honolulu, Hawaii. CD-ROM Proceedings, IEEE-Piscataway NY