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Publication Details

Hamylton, S., Silverman, J. & Shaw, E. (2013). The use of remote sensing to scale up measures of carbonate production on reef systems: a comparison of hydrochemical and census-based estimation methods. *International Journal of Remote Sensing*, 34 (18), 6451-6465.

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Keywords

scale, up, measures, carbonate, production, reef, sensing, systems, remote, comparison, hydrochemical, census, estimation, methods, GeoQuest

Disciplines

Medicine and Health Sciences | Social and Behavioral Sciences

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The use of remote sensing to scale up measures of carbonate production on reef systems: A comparison of hydrochemical and census-based estimation methods

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Abstract

The present study uses remote sensing imagery to estimate carbonate production of the complete One Tree Island reef system, Great Barrier Reef using hydrochemical (alkalinity reduction) and census-based (budgetary) methods. For five sites representing different benthic cover types across the reef system, carbonate production is determined using hydrochemical techniques that incubate substrates in a local aquarium and measure total alkalinity, total ammonia nitrogen and total oxidised nitrogen. Local estimates are scaled up to the reef-system scale using a WorldView-2 satellite image, which is ground truthed against a field dataset of 350 spatially referenced records of benthic assemblage. Annual total reef system carbonate production based on hydrochemical and census-based methods is estimated at 40 335 and 38 998 tonnes of calcium carbonate (CaCO_3) respectively. The minimal difference (0.3%) between these estimates is attributed to under representation of small carbonate producers, such as benthic foraminifera, which are difficult to incorporate in the underwater video methodology employed to populate census budgets. This finding demonstrates the utility of remote sensing for upscaling local measures of carbonate production across reef systems accurately and consistently in spite of the use of different initial estimation methods.

1.0 Introduction

Coral reef systems precipitate calcium carbonate (CaCO_3) from seawater through the active growth of calcifying organisms and consolidate these materials to form a three-dimensional structure, typically spanning an area of 1-100 km². This is built up through the active growth of calcifying organisms into carbonate reef framework that encompasses smaller particulate carbonates. Five biotic components

comprise the major carbonate producers in a reef system: scleractinian corals, coralline algae, green calcified algae, molluscs and benthic foraminifera (Montaggioni and Braithwaite 2009). The carbonate budget of a coral reef is defined as the gross biogenic carbonate production by both primary and secondary sources, as well as sediment imported into the reef minus the sum of biological, physical (carbonate sediment export) and chemical erosion processes (Scoffin 1992). The long-term stability of a reef system, in particular the integrity of the three dimensional platform that accretes over time, is fundamentally dependent on maintenance of a positive carbonate budget. In the present context of global change, reef-scale estimates of calcification are useful indicators of the influence of global processes such as ocean acidification on the capacity of reefs and their associated organisms to fix and store carbonate (Kinsey and Hopley, 1991), both as reef structural framework and in available sediment for associated landforms such as reef islands. It is therefore important to accurately quantify the calcification potential of coral reefs and their associated communities as a key constructive component of the overall carbonate budget.

Three approaches to the measurement of carbonate production that have been widely applied over the last century are hydrochemical, census-based (budgetary) and retrospective approaches. Hydrochemical approaches monitor the change in total alkalinity (A_T) of the seawater surrounding the benthic community inhabiting a reef to obtain spatio-temporally integrated measurements of metabolism (Kinsey 1978). These have been widely applied across the Great Barrier Reef and Pacific, including at One Tree Island (for review, see Kinsey 1985). Census-based approaches quantify the amount of calcium carbonate produced by a single organism per unit area of reef surface covered to estimate potential production of a reef community (Chave *et al.* 1972). These methods have been scaled up and applied to shallow reefs in Barbados (Scoffin, 1980), St. Croix in the US Virgin Islands (Hubbard *et al.* 1990), Hawaii (Harney and Fletcher 2003), Enewetak Atoll (Smith and Harrison 1977), the wider Caribbean region (Bosscher and Schlager 1992) and global fore reefs (Vescei 2001). Retrospective approaches use Holocene drill cores to estimate time-averaged values of reef accretion for a given period. Upward rates of mass accumulation are estimated through the application of radiometric dating to extracted cores and subsequent calculation of accretion rate from the thickness of a given core interval and time over which it accumulated. Much drilling work has

been carried out by the Integrated Ocean Drilling Programme and, on the Great Barrier Reef, by the International Consortium for Great Barrier Reef Drilling, which is summarised by Hopley *et al.* (2007). For each of these methods it is important to distinguish between different types of reef growth (calcification, framework production or reef platform accretion) as the nature of the reef framework will determine to a large extent how the overall platform accretes at the whole reef-system scale (Hubbard 1985). Calcification refers to the ability of corals and other organisms to convert calcium (Ca^{2+}) and carbonate (CO_3^{2-}) ions from super saturated seawater to calcium carbonate (CaCO_3) and in doing so to extend their skeletons (Kinzie and Buddemeier 1996). Framework production refers to the build up of reef framework, which may be comprised of porous structures, commonly branching or tabulate coral framework. The ability of an entire reef platform to accrete vertically is dependent on the aggregated growth of all constructive and destructive processes (Kench *et al.* 2009).

Gross carbonate production of reef platforms, can be estimated through the integration of calcification processes up levels of organisation to larger temporal and spatial scales to encompass whole reef systems. In doing so, differences in the local parameterisation of calcification can accumulate, leading to substantial variation in the estimation for whole reef system calcification. The hydrochemical and census-based approaches are commonly applied at the sub-reef scale to estimate organism and community-level production rates before being upscaled using remote sensing datasets to estimate production at higher spatial scales, including the zones such as the reef flat (Andréfouët and Payri 2000), reef platform (Hart and Kench 2007), regional reef complexes such as the North Florida reef tract (Moses *et al.* 2009) and for global reef systems (Vecsei 2004). The aim of this study is to compare upscaled estimates of carbonate production for One Tree Island based on hydrochemical and census-based measurements using additive scaling methods that linearly sum up hierarchical levels of organisation (Hatcher 1997). These upscaling methods, which assume that the metabolism of coral reef benthos is additive through increasing spatial scales, has been validated by several remote sensing studies (Andréfouët and Payri 2000; Vecsei 2001; Hart and Kench 2007). Such a comparison highlights the implications of decisions about local measurement techniques for reef-scale estimations of carbonate production.

1.1 Study Site

One Tree Island is part of the Capricorn-Bunker group approximately 80 km east of port Gladstone on the Queensland coastline (Figure 1). The raised rubble cay island (area 0.07 km²) has accumulated on the windward (southeast) side of a 6 x 3 km oblong reef system that has developed on a karst-modified Pleistocene platform reef, the depth of which varies from 10.5 to 23 m below the modern reef surface (Harvey *et al.* 1979). The island is supported by a planar reef in which the lagoon has largely been infilled (depth < 4 m), shingle ramparts are evident on the reef flat and shallow, moated microatolls have developed inside all three of the sublagoons (Hopley *et al.* 2007). The carbonate production dynamics of the One Tree Island reef have been described in detail by Davies (1983), who highlights backward growth of the reef flats over sandsheets, lagoon infill and leeward extension of the western margin as the dominant modes of contemporary reef platform accretion.

Figure 1. One Tree Island reef (152°4'16.8" E; 23°29'48.573" S). Inset: Location of One Tree Island and the Capricorn-Bunker group in relation to the Queensland coastline.

2.0 Methodology

2.1 Fieldwork: Ground Truthing surveys

To ground truth the satellite image and support the census-based parameterisation, three hundred and fifty snapshots of oblique underwater video footage were collected from a boat over a wide range of

reef system coverages at One Tree Island. At each point of interest, an underwater video camera was lowered on a cable from the boat and held so that it drifted above the sea floor to record for approximately 20-30 s, yielding a camera footprint of approximately 10 sq.m. The geographical position of each footage sample was recorded with a dGPS (positional accuracy <1 m). Rapid camera deployment permitted efficient sampling of the benthic community over the large area (approximately 20 km²) of the reef system (Figure 2).

2.2 Fieldwork: Hydrochemical determination of carbonate production

The carbonate production rate of the different substrate types in the One Tree Island reef lagoon was assessed by incubating benthic cover samples taken from various locations in the lagoon in aquaria (Figure 2). Samples were collected in buckets from the lagoon bottom and transferred immediately to the One Tree Island research station laboratory where they were subdivided into three replicate samples per benthic cover type for the measurement of total alkalinity (A_T), total ammonia nitrogen ($TAN = NH_3 + NH_4^+$) and total oxidized nitrogen ($TON = NO_2^- + NO_3^-$). Each replicate was monitored in an aquarium with continuously flowing filtered and sterilized (UV) seawater until the beginning of the incubation period. Incubations lasted for 4 hours without running water during the daytime and night-time. At the beginning and end of each incubation period, water samples were extracted from each aquarium, including a control aquarium with no sample, and analyzed for A_T , TAN and TON.

A_T was measured using the Gran titration procedure (Grasshof et al., 1983), with HCl (0.05M), on weighed samples of ~20g of seawater using an automated TitraLab 840 Radiometer analytical titrator (precision > $\pm 2 \mu\text{mol kg}^{-1}$). The acid was calibrated daily using Dickson seawater certified reference material (Dickson et al., 2007). TAN was measured according to the fluorometric protocol (Holmes et al., 1999). Each sample was spiked with 1 ml of orthophthaldialdehyde (OPA) and stored in the dark for 3 hours at room temperature. A fluorometric reading was taken at a wavelength of 421 nm. The fluorescence readings were converted to ammonium concentration according to the calibration coefficients derived from measurements of 2.5 $\mu\text{mol/l}$ ammonium standard in distilled water (precision > $\pm 10 \text{ nM}$). Samples of TON were stored in 12 ml polyethylene vials and acidified with 70 μl of 0.1 N HCl to prevent biological degradation. Concentrations were measured via a colorimetric

methodology (Hansen and Koroleff , 1999) using a Lachat QuickChem 8000 flow injection autoanalyzer (precision $\geq \pm 0.02 \mu\text{M}$).

Net precipitation of CaCO_3 ($G_{\text{net}} = \text{Precipitation} - \text{Dissolution}$) per horizontal unit area was calculated according to Equation 1 as a function of the measured changes in A_T ($\Delta A_{T-\text{aq}}$), TAN ($\Delta \text{TAN}_{\text{aq}}$), TON ($\Delta \text{TON}_{\text{aq}}$), as well as changes in A_T caused by evaporation ($\Delta A_{T-\text{evap}}$) from the control aquarium over the incubation period (Δt). For every mole of CaCO_3 precipitated or dissolved, the total alkalinity is lowered or increased by two equivalent moles (Broecker and Peng, 1982). As changes in TAN and TON observed during the incubation period were very small compared to the large changes in A_T , they were not taken into account in the G_{net} calculations. Differences were calculated by subtracting the initial value from the value at the end of the incubation and therefore precipitation is $G_{\text{net}} > 0$ and dissolution is $G_{\text{net}} < 0$ (with a factor of 0.5 to convert from units of mmoles A_T to units of mmol CaCO_3). The height of water above the sediment in each aquarium during the incubation period (Z) was used to express G_{net} as a function of horizontal unit area. Finally, the annual G_{net} , in units of $\text{kg CaCO}_3 \cdot \text{m}^{-2} \cdot \text{yr}^{-1}$, was assessed by multiplying the sum of the daytime and night time G_{net} incubation values by 12 hrs (average length of day and night during the year) to get the diurnal G_{net} and multiplying the result by $100 \text{ g CaCO}_3 / \text{mol CaCO}_3 / 1000 \text{ g/kg} \cdot 365 \text{ days/yr}$.

$$G_{\text{net}} = -\frac{1}{2} \cdot \frac{(\Delta A_T - \Delta \text{TAN}_{\text{aq}} + \Delta \text{TON}_{\text{aq}} - \Delta A_{T-\text{evap}})}{\Delta t} \cdot Z \quad \text{Equation 1}$$

Figure 2. Point sample sites surveyed at One Tree Island during the fieldwork period October 26th – November 2nd, 2011. Red dots indicate sites where underwater video footage was taken; black dots indicate hydrochemical sampling sites.

2.3 Image processing

The pan sharpened Worldview-2 image, acquired on 9th December 2009, was comprised of eight wavebands each with a spatial resolution of 0.5 m. Pre-processing procedures including atmospheric correction using the FLAASH (Fast Line-of-sight Atmospheric Analysis of Spectral Hypercubes) algorithm provided in the Environment for Visualising Images (TM) software (Cooley *et al.* 2002), image masking and water column correction were applied to the satellite image to yield radiance data that could be used as input to a classification algorithm. Bathymetric information to support these corrections was provided by the Australian Hydrographic office in the form of an airborne survey flown by LADS (Laser Airborne Depths Sounder), corrected to a horizontal datum of WGS1984 and a vertical datum of Lowest Astronomical tide (Fugro, 2011). The 28 307 elevation points were subsequently interpolated to a continuous surface using a first order kriging algorithm and validated against a set of 312 bathymetric survey points collected during fieldwork with a Norcross x single beam bathymetric sounder and the accuracy was found to be high ($R^2 = 0.94$).

A supervised classification was performed using a maximum likelihood parametric rule on the corrected image bands of the One Tree reef system. Of the three hundred and fifty video

records collected, fifty were used to define training areas to supervise the image classification. The classified output was a single thematic layer composed of thirty classes that were subsequently interpreted with respect to the ground referencing dataset from the video footage records. A final map of fifteen classes was produced that encompassed both the terrestrial (three classes) and marine environment (twelve classes). The video footage records falling inside the spatial extent of this class were then extracted from the field dataset and viewed independently, with % cover of benthic components estimated visually, to facilitate interpretation and validation of the classification output. The overall accuracy of this map was calculated as the proportion of video ground referencing points collected *in-situ* that were assigned to the same class as the map (Congalton 1991).

2.3 Hydrochemical technique

Where it was not possible to measure carbonate production directly using field samples, this study utilised published values of hydrochemically-derived reef calcification that were established from repeat field measurements at One Tree Island (Kinsey 1985). As with the techniques employed in the present field study, these studies estimated the net gain in fixed organic carbonates CaCO_3 , G_{net} of the reef community for a given zone was estimated from changes in the alkalinity of the overlying seawater for a given slack tidal period (Kinsey 1978).

Map classes relating to each reef zone were summed to yield a measure of the area covered and, as with the census-based technique, upscaling proceeded by summing in a linear manner across the reef community production values for each reef zone:

$$G_{net} = 0.01 \times \sum_{j=1}^n (P_j \times \%cover) \quad \text{Equation 2}$$

To compare the two methods of upscaling, the estimated overall carbonate production of the system was calculated using each method, as well as the carbonate production for each mapped benthic cover class.

2.4 Census-based technique

This study utilised published values of potential carbonate production, P , for individual biotic components that had been established in a commensurate Indo-Pacific field setting (Chisholm 2000,

Harnery and Fletcher 2003 and Hart and Kench 2007) with area statistics estimated from the 350 video snapshots of the seafloor. These were calculated as either the product of organism turnover rate and the mass of the organism per unit area occupied (D) (Equation 3):

$$P = \frac{B}{A} \times D \quad \text{Equation 3}$$

or the calcium carbonate mass per unit volume of the organism (ρ) multiplied by the upward growth rate (C) (Equation 4).

$$P = C \times \rho \quad \text{Equation 4}$$

For each map class, potential production values were converted to gross production, G_c , by summing across the relative proportion of the biotic components that made up the characteristic assemblages (P_i) (Equation 5):

$$G_c = 0.01 \times \sum_{i=1}^n (P_i \times \%cover) \quad \text{Equation 5}$$

The relative proportion of each biotic component was ascertained from the field dataset of 350 video footage records. Records were subdivided on the basis of the mapped benthic cover class in which they fell and the average coverage was calculated for each benthic cover class. Finally, the gross production of the One Tree Island reef system was estimated by summing across the map classes.

3.0 Results and Discussion

3.1 Fieldwork

Calm weather conditions during the fieldwork period permitted spatially extensive sampling of each reef zone. The 350 snapshots of video footage provided a detailed record of benthic cover across each of the reef zones at One Tree Island. Statistically discernable variation among the coral community growth forms was evident from the footage collected, with massive corals around many of the more developed lagoon patch reefs, deeper lagoon reticulate network was comprised of branching corals, the reef flat supported a mixture of branching and massive growth forms and the outer reef largely supported branching corals. These groupings were in line with the characteristic coral growth profiles recorded by Davies (1983).

3.2 Fieldwork: Hydrochemical determination of carbonate production

Results of the carbonate flux measurements are summarised in Figure 3. All benthic cover types precipitated CaCO_3 during the daytime and dissolved CaCO_3 during the night-time. While the night time rates of CaCO_3 dissolution for each benthic cover type were not significantly different from their mean (Kruskal-Wallis, $p=0.157$), the daytime rates of CaCO_3 precipitation were nearly 3 to 4 times greater in samples from sites 1 and 5 than in samples from sites 2-4 (Kruskal-Wallis test, $p=0.001$). Table 1 incorporates the estimated annual rates of CaCO_3 production for each of the benthic cover types sampled in the One Tree reef lagoon (those not marked with an asterisk).

Figure 3. G_{net} values measured in the daytime and nighttime incubations of the different benthic cover types sampled in the One Tree reef lagoon during November 2011 (see Figure 2 for sample locations). Error bars indicate the range of the standard error estimated from measurements of three replicates for each cover type.

3.3 Image processing

The image classification generated a clear and accurate representation of the heterogeneity of shallow reef habitats apparent in the WorldView2 image (Figure 4). Overall accuracy of the habitat map,

measured in terms of the number of patches correctly identified divided by the total number of patches in the validation assessment (Congalton 1991), was found to be 81 %.

Figure 4 Benthic cover map generated from a supervised classification of the WorldView-2 image of One Tree Island.

3.4 Upscaled estimates of carbonate production using the hydrochemical and census-based techniques

The estimates of total reef system carbonate production were 40 335 tonnes per year and 38 998 tonnes per year generated from hydrochemical and census-based methods respectively (Tables 1 and 2).

Reef zone	G_h^* (kg m ⁻² yr ⁻¹)	Associated map classes (area covered)	Gross production, ΣG_h (kg yr ⁻¹)
Algal ridge	4	Algal pavement (0.96 km ²)	$38 \times 10^5^*$
Coral-algal zone	5	Reef flat bommies on sand (2.44 km ²) Algal assemblage on sand (0.97 km ²)	$16 \times 10^6^*$
Rubble/sanded reef flat	0.5	Reef flat sand (1.61 km ²) Reef flat consolidated rubble (0.53 km ²)	22×10^4
Coral/algal hard substrate	10	Live coral (outside lagoon) (2.23 km ²)	$10 \times 10^6^*$
Open lagoon, occasional patch reefs (shallow lagoon)	1.5	Lagoon sand with coral patches (1.61 km ²)	$24 \times 10^5^*$
Lagoon sand	0.3	Lagoon sand (1.12 km ²) Shallow lagoon sand (0.1 km ²)	36×10^3
Reticulate lagoon reefs	4	Live coral (inside lagoon) (1.83 km ²) Total reef system G_c (kg yr ⁻¹)	43×10^5 37×10^6 (49,335 tonnes)

* G_h parameterized using values from Smith and Kinsey (1976) and Kinsey (1977, 1979).

Table 1. Hydrochemically derived measures of annual carbonate gain for zones of the One Tree Island reef system, scaled up using the classified WorldView-2 image. (* G_{net} parameterised using values from Kinsey, 1985, Smith & Kinsey, 1976)

Map class	<i>n</i>	Biotic assemblage (% cover)	Map class gross production*
Algal assemblage on sand	32	Live coral (2%) Macroalgae (20%) Sand (65%) Dead coral framework (1%) Algal mat (10%) Rubble (2%)	39×10^5
Algal pavement	15	Live coral (10%) Calcified algae (10%) Dead coral framework (80%)	43×10^5
Deep outer reef patches on sand	39	Live coral (10%) Consolidated reef carbonate platform (75%) Calcified algae (5%) Rubble (10%)	39×10^5
Fore-reef coral spur with coralline algae	21	Live coral (60%) Calcified Algae (5%) Rubble (10%) Sand (5%) Dead coral (20%)	62×10^5
Upper fore-reef slope coral, rubble and sand	25	Live coral (65%) Sand (5%) Rubble (15%) Dead coral framework (15%)	58×10^5
Lagoon sand	31	Sand (90%) Algae (4%) Rubble (6%)	74×10^4
Lagoon sand with coral patches	28	Live coral (20%) Algae (5%) Sand (65%) Rubble (5%) Dead coral framework (5%)	62×10^5
Lagoonal reef	50	Live coral (70%) Soft coral (10%) Dead coral framework (20%)	55×10^5
Live coral (outside lagoon)	12	Acropora (35%) Branching (35%) Dead coral framework (15%) Sand (12%) Rubble (3%)	47×10^5
Reef flat bommies on sand	52	Live coral (30%) Calcified algae on coral framework (10%) Algae (5%) Rubble (5%) Sand (40%) Dead coral framework (10%)	76×10^5
Reef flat consolidated rubble	12	Consolidated rubble (100%)	19×10^4
Reef flat sand	33	Sand (94%) Algae (4%) Rubble (1%) Total G_c excluding fore-reef classes (kg yr^{-1})	97×10^4 35×10^6 38,998 tonnes

* G_c parameterized using values from Chisholm (2000), Harner and Fletcher (2003), and Hart and Kench (2007), *n* = number of video footage samples.

Table 2. Census-based measures of annual carbonate gain for biotic components of the One Tree Island reef system, scaled up using the classified WorldView-2 image. (* G_c parameterised using values from Chisholm 2000, Harner and Fletcher 2003 and Hart and Kench 2007, *n*= number of video footage samples).

Of the twelve benthic cover classes mapped, estimates of carbonate production were generated using both hydrochemical and census-based methods for nine of the classes (three of the classes covered

fore-reef areas, for which ocean mixing limits the application of hydrochemical methods). It can be seen from Figure 5 that for these nine cases where both methods were employed, hydrochemical estimates of reef production were consistently higher than census based estimates (in seven cases out of the nine). Both approaches estimated that the least productive classes mapped were the lagoon sand and the reef flat sand, which act as sink areas for carbonate that has been transported from production zones elsewhere on the reef platform.

Figure 5. Comparison of hydrochemically and census-based derived estimates of carbonate production for each of the benthic cover classes mapped at One Tree Island (note: there are no hydrochemical estimates for the fore-reef zone due to methodological limitations).

4.0 Discussion and conclusions

Overall estimates of yearly gross carbonate production for the One Tree Island reef system equated to $2.20 \text{ kgCaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ for the hydrochemical method and $2.16 \text{ kgCaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ for the census-based method both of which exceed the hydrochemically-derived value of $1.5 \text{ kgCaCO}_3 \text{ m}^{-2} \text{ yr}^{-1}$ for the entire reef system (Kinsey 1985) and fall in between published values for the different reef zones (ranging from 0.6 for the leeward margin to 7.3 for the windward margin) (Davies 1983). It is likely that the estimates of carbonate production per unit area are larger than those arrived at by Kinsey (1985) due to the difference in benthic cover maps employed to upscale the hydrochemical measurements across the entire reef system. A comparison of the maps used in both studies reveals three important differences that would have implications for the estimates arrived at through the

upscaling process. Firstly, the maps used by Kinsey were comprised of 7 benthic cover types while those generated from classifying the satellite image encompassed a greater range of benthic diversity, incorporating 12 benthic cover types. Secondly, it is clear that areas that were mapped as homogenous regions of consistent benthic character by Kinsey were mapped with a higher degree of spatial heterogeneity in benthic using the satellite imagery. For example, a large area of the lagoon mapped as the single class “open lagoon with submerged pinnacles” was mapped as “lagoon sand”, “lagoon reef”, “algal assemblage on sand” and “lagoon sand with coral patches” using the satellite imagery. Thirdly, the relative proportion of cover mapped for the benthic cover classes that produce carbonate at a faster rate appears to be lower in the earlier study (e.g. within the lagoon the Kinsey study mapped 0.9km² of reef while the same figure mapped from the satellite image was 1.83km²). Despite the occurrence of bleaching episodes in the intervening period that may have reduced live coral cover (Hoegh-Guldberg *et al.* 2005) and observed reductions in net calcification at a long term monitoring site (Silverman *et al.* 2012), these differences arise because of the increased spectral detail available from the multiple image wavebands of the satellite image. While this detail enables a notable improvement on historical reef maps derived from air photos, which were unavoidably generalised, it highlights the methodological differences in the upscaling component of the procedure for estimating carbonate production of entire reef systems. Nevertheless, estimates arrived at in the present study equate to a cumulative yearly production for the entire reef system of 40 335 tonnes per year and 38 998 tonnes per year generated from hydrochemical and census-based methods respectively. The minimal difference (0.3%) between these values is remarkable and, when the upscaling component is controlled for and only the local method for measuring carbonate production is varied, this testifies to the potential for remote sensing technology for accurately and consistent upscaling of carbonate production measures across reef systems. This is likely due to improvements in both the application of remote sensing technology to coral reef systems (Goodman *et al.* 2012) and field based measures of community calcification (Silverman *et al.* 2007; Shamberger *et al.* 2011).

It has been suggested that the reef flat holding zone requires a 4000 tonne transference of carbonate material from the reef front every six to ten years (Davies 1983) and on the basis of the census based estimates (an additional volume of approximately 11.1 tonnes per year), the potential production of the

reef front is adequate to meet this. It also exceeds the regional fore-reef estimates of carbonate production for the Great Barrier reef, which range from 5 to 9.8 kgCaCO₃ m⁻² yr⁻¹ (Vescei 2001), however, little is known about how much of this is retained in the One Tree reef system budget. Intertidal dissolution, mechanical and biological erosion are evident in the form of undercut notches, interconnected reef flat pool systems and sharp coral outcrops, particularly on the windward side. Much of this will also be transported either to the lagoon sink or, following the dominant direction of water movement (Ludington 1981), be exported over the leeward margin.

In seven of the nine benthic cover classes mapped, the hydrochemical methods estimated a higher carbonate production value than the census-based methods, resulting in a total disparity for these seven classes of 1 337 tonnes. Minor differences between parameterisations of carbonate production rates at the local community scale were amplified throughout the upscaling procedure, as is commonly the case with remotely sensed datasets (Van Gardigan *et al.* 2007). Of the five major carbonate producing biotic components (coral, coralline algae, green calcified algae, molluscs and benthic foraminifera, as per Montaggioni and Braithwaite 2009), it is possible that the census-based approach failed to account fully for the molluscs and benthic foraminifera, the presence of which are difficult to discern from the footage taken using the drop camera. Elsewhere on the Great Barrier Reef, benthic foraminifera have been found to contribute up to 30% of cay sediment (Yamano *et al.* 2000) and this may underpin the shortfall in carbonate production estimates derived using the census-based approach. It may also be the case that some of this disparity can be attributed to classification error associated with the processing of the satellite image.

A key methodological difference between the hydrochemical and census-based approaches is the question of whether or not they encompass the fore-reef zone. The attribution of chemical changes in the seawater to metabolic processes of a spatially defined benthic community requires low-flow or standing water conditions in which limited mixing occurs with water from adjacent zones (Kinsey 1978). With the exception of one Pacific reef example (Kinsey 1985), hydrochemical measurements have therefore largely been restricted to the reef flat and lagoon during the slack water tidal ebb, which limits their utility for estimates encompassing the whole reef system.

Conversely, census-based estimates have been successfully applied to regionally idealised fore-reefs in each of the coral seas (Vescei 2001). The fore-reef emerged as one of the most productive zones and a key source of carbonate for deposition on other reef system components (Kleypas *et al.* 2001).

Where possible, recent calcification rates have been used to parameterise the carbonate production models, however, one key limitation of this study is the reliance on calcification rates published in the 1970s and 80s for those benthic substrates (six out of the ten substrates modelled), where recent measurements were not conducted. This introduces a temporal disparity in the carbonate production estimates being compared, the older measures of which have likely fluctuated as reef community structure has changed. These will continue to be influenced as atmospheric CO₂ levels are expected to rise to 450 ppm by 2030-2040, driving responses in both coral reef communities and ocean chemistry (Veron *et al.* 2009; Hoegh-Guldberg *et al.* 2007). While the best available data is employed for the time being, it highlights the need for regular in-situ hydrochemical measurements of community calcification across a range of representative benthic substrates. With respect to the census-based approach, resulting observable variations in the composition of benthic communities, such as reduction in coral cover as a result of bleaching, can be adequately captured and incorporated by the spatial and spectral information provided by the WorldView-2 image, as has been the case with bleaching induced coral mortality as a result of the El Nino Southern Oscillation at the Uva Island reef, Panama (Eakin 2001). Other oceanographic consequences of climate change including sea-level rise and ocean acidification (Kleypas and Langdon 2006) remain more difficult to account for. Evidence from the skeletal records of 328 massive *Porites* colonies across the Great Barrier Reef suggests a reduction of approximately 14% in scleractinian calcification that can partly be attributed to ocean acidification (De'ath *et al.* 2009).

Despite multiple potential sources of error (estimation of areal coverage of benthic substrates from the video footage, classification error of the satellite image, temporal disparity between hydrochemical and census-based parameterisations), it has been demonstrated here that across large scales of integration, different approaches to the local parameterisation of community calcification yield similar estimates of carbonate production at the reef system scale. Estimates of

contemporary production vary by several orders of magnitude between different reef systems depending on type of substrate, growth and cover rates, however, comparisons made here between the scaled up hydrochemical and census-based approaches for a single reef system reveal remarkable consistency. While these could profitably be improved by either using more detailed approaches to sampling census components of the reef carbonate producers (e.g. foraminifera) or extending hydrochemical measurements to the fore-reef where favourable conditions will allow, this study provides a compelling example of the accuracy and consistency with which remote sensing datasets can be used to upscale local measures of carbonate production.

5.0 References

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6.0 Acknowledgements

We thank Professor Ken Caldeira and Dr Kenneth Schneider from the Department of Global Ecology, Carnegie Institution for Science, Stanford, California for help with coordinating the fieldwork associated with this study. This work has been made possible by a University of Wollongong Near-Miss grant, 2011. Professor Valerie Harwood and Jennifer Reiffel are thanked for assistance with fieldwork.