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Estimating regional coral reef calcium carbonate production from remotely sensed seafloor maps

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ABSTRACT

Carbonate production on coral reefs is responsible for the provision of beach sands, for the maintenance of seawater chemical balances and for the growth of reef structure and associated habitat complexity. Key carbonate producers including hard coral, crustose coralline algae, foraminiferal sand and *Halimeda* were mapped from satellite imagery (spatial resolution 2.5 m, mean overall accuracy = 81%) and an upscaling model was applied to estimate carbonate production. A sensitivity analysis was conducted to evaluate the influence of employing different calcification rates for live coral on the upscaling model. Contemporary coral reef carbonate production for the 21 reef platforms of the Capricorn-Bunker Group (southern Great Barrier Reef) is estimated to be between 489,000 and 659,000 t per year based on seawater chemistry, community composition, calcification rates and reef structural complexity (rugosity). The upscaling model was relatively insensitive to different parameterisations of live coral calcification employed, probably due to live coral being a relatively minor contributor by area (approximately 18% of total reef area throughout the study region). This suggests regional scale seafloor characteristics, such as percentage of area dominated by substrates prone to dissolution (e.g. coral rubble), have a strong bearing on calcium carbonate production and need to be given greater consideration The upscaling framework presented provides a new method for quantifying regional carbonate production that could be applied globally, and provides a valuable baseline against which future changes to carbonate production in this region can be assessed.

1. Introduction

Calcium carbonate production underpins many of the goods and services provided by coral reefs, including the provision of beach sands, habitat for fish and chemical balancing of seawater (Andersson and Gledhill, 2013). Over geological timescales (i.e., centuries or millennia), calcium carbonate production leads to the build-up of substantial carbonate reef structures. Calcium carbonate production is fundamentally determined by the ability of calcifying organisms that inhabit coral reefs to convert calcium and carbonate ions derived from seawater into a hard, calcified skeleton. These organisms include coral, crustose coralline algae, foraminifera and calcified algae such as *Halimeda* (Fig. 1). This is broken down into carbonate sediments and bound into interstitial spaces between skeletal structures, with loose materials becoming overgrown and encrusted by coralline algae to form large, solid structures (Hubbard, 1997). Reef structures undergo growth pulses that are interspersed with erosive periods when sea level or environmental conditions are not conducive to coral growth. A coral reef can therefore be thought of as a three-dimensional physical structure, which has been built up and continues to grow over decadal to millennial time scales, as a result of the accumulation of calcium carbonate laid down by corals and other organisms.

The ecological zonation of carbonate producing communities on coral reefs has long been recognised (Done, 1983; Goreau, 1959). The geographical distribution of calcium carbonate producers around an individual reef platform is driven by local environmental factors, such as wave energy, light availability and degree of turbidity (Done, 1982). Attempts to estimate calcium carbonate production must therefore

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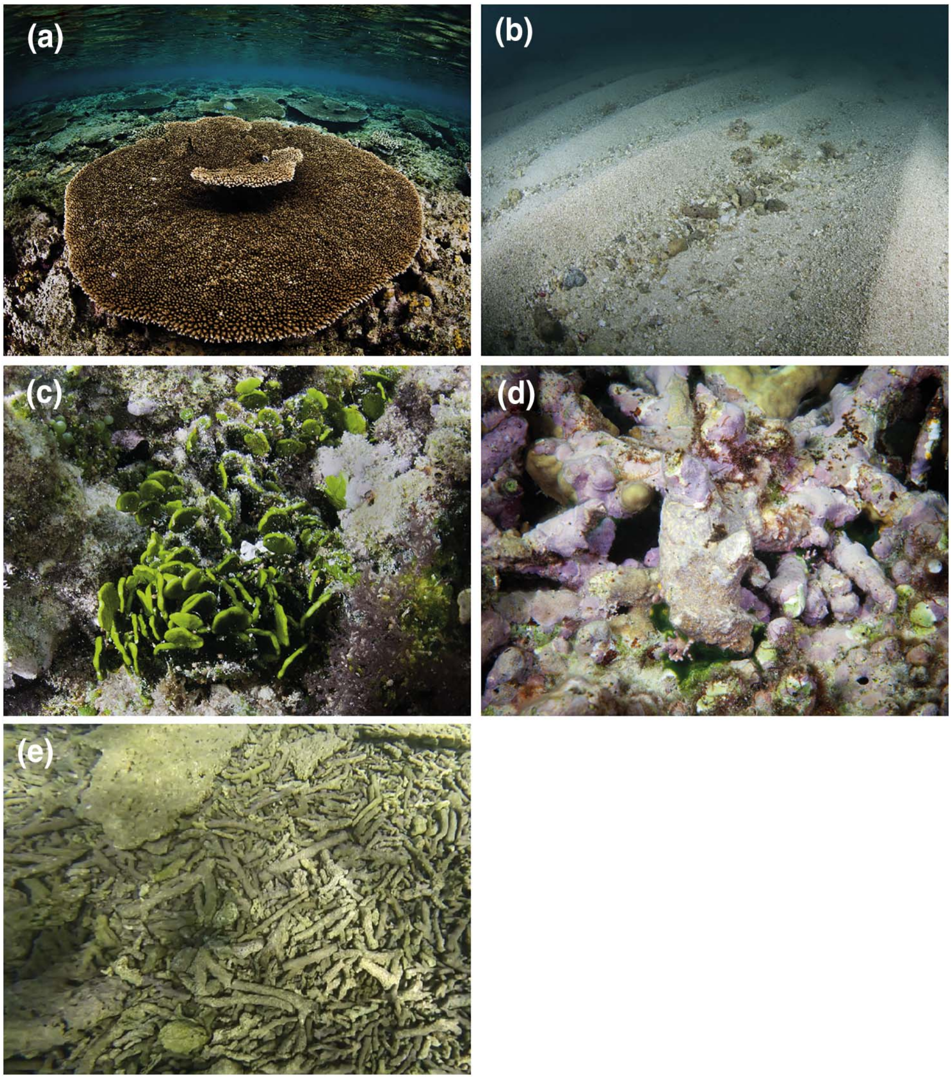

Fig. 1. Coral reef community components that produce calcium carbonate and their associated substrates that are prone to dissolution, including (a) live coral, (b) carbonate sand including foraminifera, (c) *Halimeda* macroalgae, (d) crustose coralline algae, and (e) dead coral rubble.
(Photo credit: Matthew Smith.)

account for the geographical variation of these factors across reef platforms. This can be achieved by estimating carbonate production at scales that correspond to reef geomorphological units, or zones. By doing this, it is possible to evaluate the functional implications of reef carbonate budget changes in terms of the relative growth or evolution of the reef. For example, the volume of sediment available to be delivered to a lagoon, beach or island can be better estimated when the total carbonate production of the whole reef front is known, as opposed to a localised area covered by a field survey.

Remote sensing has been employed to map reefs and their benthic communities in detail and, in doing so, to upscale localised measurements of carbonate production across individual reefs. Upscaling studies have estimated reef carbonate production for relatively large ($> 103\ km^2$) geographical areas, including reef flats in Moorea (Andréfouët and Payri, 2001), regional groups of reefs, such as the Northern Florida Reef Tract (Moses et al., 2009), the Torres Strait (Leon and Woodroffe, 2013), the Chagos islands (Perry et al., 2015b) and, at the global scale, for both forereefs (Vecsei, 2001) and entire reef provinces (Vecsei, 2004). These studies have been supported by improvements in spatial data quality over the last decade, particularly with respect to increasing spatial and spectral resolution of satellite images that have allowed calcifying benthic communities to be mapped in greater detail with higher levels of accuracy (Andréfouët and Payri, 2001; Hamylton et al., 2013b). In turn, these improvements have allowed estimates of carbonate production to be determined across larger areas of reef. The incorporation of measures of reef community structural complexity, or rugosity, into estimations has also had an important bearing on estimates of reef-scale carbonate production (Hamylton, 2014; Perry et al., 2013).

The distribution, extent and functioning of calcium carbonate producing organisms is affected by anthropogenic and natural stressors (Kleypas and Yates, 2009). Understanding the magnitude of reef carbonate budget changes, and how they have changed within and between reef-building regions has thus been a focus of considerable recent research interest. This has encompassed spatio-temporal assessments of reef carbonate production, that elucidate how production varies both across different reef zones (i.e., forereef, lagoon, reef flat etc.) (Kinsey and Hopley, 1991; Kinsey, 1983; Smith and Kinsey, 1976), in relation to gradients in environmental controls, such as water depth and wave energy (Hamylton et al., 2013a) and; considerations of how carbonate budgets may respond to future climate change drivers (Hamylton, 2014; Januchowski-Hartley et al., 2017; Kennedy et al., 2013; Perry and Morgan, 2017).

The aims and objectives of this study are:

1) To generate a regional scale (approx. 130 km × 50 km) assessment of coral reef carbonate production for the 21 reefs of the Capricorn-Bunker Group in the southern Great Barrier Reef, Australia, from a combination of field survey and satellite image processing;
2) Where possible, to incorporate structural complexity into estimates