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Fluctuations in coral health of four common inshore reef corals in response to seasonal and anthropogenic changes in water quality

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Environmental drivers of coral condition (maximum quantum yield, symbiont density, chlorophyll *a* content and coral skeletal growth rates) were assessed in the equatorial inshore coastal waters of Singapore, where the amplitude of seasonal variation is low, but anthropogenic influence is relatively high. Water quality variables (sediments, nutrients, trace metals, temperature, light) explained between 52 and 83% of the variation in coral condition, with sediments and light availability as key drivers of foliose corals (*Merulina ampliata*, *Pachyseris speciosa*), and temperature exerting a greater influence on a branching coral (*Pocillopora damicornis*). Seasonal reductions in water quality led to high chlorophyll *a* concentrations and maximum quantum yields in corals, but low growth rates. These marginal coral communities are potentially vulnerable to climate change, hence, we propose water quality thresholds for coral growth with the aim of mitigating both local and global environmental impacts.

1. Introduction

Over one third of the world's coral reefs are situated in South East Asia and they host some of the highest levels of marine biodiversity on Earth (Burke et al., 2002). They are also threatened by human activities including over exploitation, coastal development and pollution (Bryant et al., 1998; Burke et al., 2002). Singapore's coral reefs, home to 255 hard coral species, lie within the port limits of one of the world's busiest harbours (Huang et al., 2009). Land reclamation and the amalgamation of reef-fringed islands for port construction and oil refineries have resulted in a loss of over 60% of Singapore's original reef area (Chou, 2006). Ongoing coastal development and dredging of shipping channels, which release large volumes of sediments, associated nutrients and trace metals into the marine environment, are primary threats to coral reef health in Singapore (see review in Todd et al., 2010).

Singapore's coral reefs are dominated by sediment-tolerant coral taxa which are generally restricted to the upper 5 m of the reef slope due to low light levels (Huang et al., 2009; Tun et al., 1994). Sediment loads can stress corals both in suspension, which increases turbidity and limits light penetration (Rogers, 1990; Wolanski and De'ath, 2005), and when deposited (Lui et al., 2012). Limited light penetration reduces photosynthesis and energy production by the symbiont algae within the coral (Anthony and Connolly, 2004; Falkowski et al., 1990), whereas deposited sediments may smother corals (Loya, 1976), reduce hard substrate availability thereby limiting larval settlement (Fabricius et al., 2003), and increase the prevalence of tissue infections (Bruno et al., 2003). Some species have developed morphological and/or physiological mechanisms to cope with increased sediment loads, which allow these corals to survive, and in some cases dominate, coral reefs exposed to sediments (Erftemeijer et al., 2012). For example, foliose corals such as *Turbinaria* develop funnel shapes which channel and concentrate sediments to central regions of the colony thereby limiting the surface area affected by sedimentation (Sofonia and Anthony, 2008). Other corals such as *Goniastrea* are known to increase their heterotrophic feeding capabilities in response to limited light (Anthony, 2000). Despite limited coral growth at depth due to high light attenuation and high sedimentation rates (Dikou and van Woesik, 2006; Lane, 1991; Low and

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Chou, 1994), there is recent evidence that coral cover and biodiversity in Singapore's shallow waters has not changed over the last ~25 years (Tun, 2013). These data suggest that local corals may have reached equilibrium with contemporary water quality conditions, considered by many to be marginal for reef growth (Browne et al., 2012).

Despite being potentially resilient, coral reefs in Singapore may be surviving at the edge of their environmental tolerances and therefore be more vulnerable to the effects of climate change. At present, there are no long-term in situ data that document how local corals respond to environmental conditions, including fluctuations in sediment loads and water quality. Such a data set would provide key information on coral condition in Singapore in response to environmental fluctuations, improve current understanding on how these corals have adapted and/or acclimated to marginal reef growth conditions, and address concerns on reef vulnerability to climate change. Variations in coral condition and physiology with light (Falkowski et al., 1990; Hennige et al., 2008, 2010) and temperature (Anthony and Connolly, 2007; Coles and Jokiel, 1977; Crabbe, 2007; Fagoonee et al., 1999) are well documented, but long-term studies (>6 months) of coral condition that cover a substantial spatial area (>1 km) and measure a number of key environmental drivers, are rare. Notable exceptions include: Hennige et al. (2010) who documented changes in community composition, coral metabolism and symbiodinium community structure along environmental gradients in Indonesia; Fagoonee et al. (1999) who monitored symbiont density in *Acropora* in the field for over 5 years in response to light, sea water temperatures and seasonal changes in nutrient concentrations; Fitt et al. (2000) who measured tissue biomass and symbiont density for five hard coral species for up to 4 years, and Cooper et al. (2008) who found that variations in symbiont density were strongly associated with sea water temperatures and water quality. These studies all indicate that coral physiology and coral condition are influenced not only by light and temperature, but by seasonal and/or spatial variations in water quality. In Singapore, where the amplitude of seasonal environmental variation is low, water quality is the primary threat to the health and survival of corals. A comprehensive assessment of spatial and temporal variations in water quality with coral condition would further current understanding of local coral responses and reef resilience.

Two key aspects of water quality that have received the most attention in recent years are sediments and nutrient loads. A review of the impacts of sediments on coral reefs by Risk and Edinger (2011) summarises research findings in this field to date and provides key indicators of sediment stressed reefs, which include low species diversity and live coral cover, low coral recruitment rates, high Ba/Ca ratio in coral skeleton as well as high coral extension rates but low skeletal densities. High nutrient loads on coral reefs were also found to lead to changes in coral growth with high levels of nitrogen resulting in stunted growth whereas high levels of phosphorus caused increased linear extension but declines in skeletal density (Koop et al., 2001). The combined effects of high sediments and nutrients have been less well researched, although they are thought to act antagonistically: with sediments typically stunting coral growth and nutrients increasing growth (Edinger and Risk, 1994; Edinger, 2000). In a recent review by Risk (2014) a range of assessment techniques to determine sediment and nutrient stress on reefs are identified which include the use of $\delta^{15}N$ in coral tissue (Risk et al., 2009). This promising retrospective technique is, however, relatively new and requires more extensive testing under different environmental scenarios.

In the present study, we analyse four parameters of coral health in relation to fluctuations in nutrient and sediment loads. We measured coral photo physiology (maximum quantum yield, symbiont density and chlorophyll *a* content) as well as coral growth rates. These indicators of coral health allowed us to follow changes over shorter sampling periods (non-retrospective) and test the effects of seasonal fluctuations in water quality. Specifically, the objectives of the paper were to: 1. Assess spatial and temporal variations in coral conditions, 2. Identify key environmental drivers of coral condition, and 3. Identify water quality threshold values for coral growth in Singapore's coastal waters.

2. Materials and methods

2.1. Study species and field sites

In February 2012, three colonies of *Merulina ampliata*, *Pachyseris speciosa* and *Platygyra sinensis* were collected from three sites around Singapore (Kusu Island, Pulau Hantu, Labrador Park; Fig. 1) at 3–4 m depth at Lowest Astronomical Tide (LAT). In addition, three colonies of *Pocillopora damicornis* were also collected from Kusu Island. These corals were selected as they represent both abundant (>5% cover), resilient species (e.g. *M. ampliata*) and rarer, sensitive species (e.g. *P. damicornis*), as well as range of coral morphologies. Each colony was broken into fifteen fragments (approximately 5 cm × 5 cm), and mounted either on to a plastic grid or wall plug (for *P. damicornis*) using underwater epoxy resin (Epoputty, UK). Once the resin had hardened, all coral fragments at each site (a total of 135 fragments each at Pulau Hantu and Labrador Park, and 180 fragments at Kusu Island) were secured onto a frame positioned on the reef slope at 3 m. Following a one month recovery period, two thirds of the coral fragments were removed from each site with one third going to each of the other two sites. This reciprocal transplantation resulted in each site having five fragments of the same nine genotypes for *M. ampliata*, *P. speciosa* and *P. sinensis* and three genotypes for *P. damicornis*. Coral fragments remained in situ for one year and health was monitored monthly.

The three field sites in Singapore are characterised by different sedimentary regimes, exposure to natural waves, and anthropogenic influences including ship wakes and dredging activities. Turbidity and light at Kusu Island (at 3 m LAT; N 1.22838, E 103.85525), the most eastern and exposed site, typically ranged from 1 to 3.0 mg l^{-1} with maximum peaks reaching 40–50 mg l^{-1} and 50 to 400 PAR (photosynthetically active radiation), whereas Pulau Hantu, the most sheltered westerly site (N 1.22640, E 103.74675), had lower maximum peaks (20–30 mg l^{-1}) and higher light penetration (100–500 PAR). The third site at Labrador Park is situated next to the mainland, approximately 500 m east of a land reclamation site and busy harbour (N 1.26636, E 103.80015). During 2012, this site was influenced by dredging at the land reclamation site as well as ship-wakes from fast moving ferries (pers. Obs.). Consequently, turbidity levels typically ranged from 5 to 20 mg l^{-1}, with maximum peaks reaching >150 mg l^{-1} and light levels were lower (0–300 PAR) compared to Kusu Island and Pulau Hantu.

2.2. Environmental variables

Temporal variations in water quality, sediment accumulation rates (SAR), light penetration and sea surface temperature (SST) were collected twice each month. Water quality parameters included chlorophyll *a*, suspended sediment concentration (SSC), alkalinity, ammonia (NH_3), nitrate (NO_3), phosphate (PO_4), silicates, total nitrogen (TN), total phosphate (TP) and trace metals (aluminium, silver, cadmium, copper, iron, nickel, lead, and zinc). Water samples (5 L) were collected by divers next to the floating frames at 3 m at LAT. For chlorophyll *a*, triplicate water samples (250 ml), stored in dark bottles during transportation, were