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Coral reef degradation and metabolic performance of the scleractinian coral *Porites lutea* under anthropogenic impact along the NE coast of Hainan Island, South China Sea

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ABSTRACT

Hainan's coast provides favorable climatic, geochemical and biogeographic conditions for the development of extensive coral reefs in China. Observations in five reefs along the NE coast of Hainan showed, however, that the overall density of mobile macrofauna is low and key functional groups such as browsing, scraping or excavating herbivore fish are missing altogether. Coral diseases, partial mortality or tissue degradation are abundant and growth of macroalgal space competitors extensive. Signs of eutrophication, siltation and destructive fishing practices are evident resulting in a strongly altered environment unfavorable for coral recruitment success and survival. Acclimation to the anthropogenically altered conditions in the massive coral *Porites lutea* occurs at the cost of a decreased photosynthesis: respiration ratio reducing the regenerative capacity of these key framebuilding organisms. Even though, on the organismal level, corals are able to cope with these stressful conditions, a shift is imminent on the ecosystem level from a coral reef to a macroalgae-dominated community if land-based disturbance prevails unabated.

1. Introduction

It is estimated that one third of all reef-building coral species are at risk of being extinct as a result of climate change and local ecosystem impacts (Carpenter et al., 2008). Amongst the most severe and acute local threats to coral reefs are the impacts of overfishing and pollution (Hodgson, 1999; Wilkinson, 2004; Hughes et al., 2007), which significantly lower a reef's resilience hence making it more subjected towards global changes in temperature and acidification (Carpenter et al., 2008). In places where they co-occur reef degradation has been shown to have deleterious impacts on coral communities (Lapointe et al., 1997; Littler et al., 2006; Mumby et al., 2007). Corals and algae are important primary producers co-occurring in tropical shallow water reefs (Crossland et al., 1991; Hatcher, 1997). As space competitors (Littler and Littler, 1985; Lapointe et al., 1997), their co-existence is balanced by nutrient supply (bottom-up control) and grazing (top-down control), where the competitive advantage of fleshy macroalgae in terms of nutrient-enhanced growth is opposed by their greater grazing susceptibility. Changes in nutrient status and grazing can therefore have deleterious effects tilting the balance of corals to algae in reefs (Hughes, 1994; Bellwood et al., 2004), however, the rates and kinds of change are difficult to predict, as the interplay of direct and indirect effects is complex (Glynn, 1988), feedback loops result in non-linear system responses, and coral- or algal dominated communities are only two out of several possible alternate states (Rogers, 1990;Bellwood et al., 2004; Pandolfi et al., 2005).

Before phase shifts occur, changes in water quality already impact coral physiology, and corals have shown a wide range of responses to disturbances including self-cleaning via mucus production in waters subjected to sedimentation (Schuhmacher, 1977; Rublee et al., 1980), proliferation of the corals' symbionts and photosynthetic pigments in nutrient rich and turbid waters (Roder et al., 2011; Sawall et al., 2011), or the shift from autotrophic to mixotrophic or even heterotrophic nutrition if photosynthesis is not sufficient to maintain energy demands (Muscatine et al., 1989; Roder et al., 2010). Further responses to human induced ecosystem changes comprise reduced coral

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growth (Bak, 1978; Marubini and Davies, 1996; Ferrier-Pagès et al., 2000), and declines in reproduction (Loya et al., 2004).

Corals have been shown to resist competition with macroalgae even in eutrophied waters, when sufficient grazing pressure on algae is present (Aronson and Precht, 2001; Aronson et al., 2002). Sometimes, the original grazers might not even be present any more, but replaced by other species such as sea urchins (McClanahan and Muthiga, 1988; Steneck, 1998). They can in cases of extensive overfishing become the only grazing control of algae (Ogden et al., 1973; Levitan, 1988) and may, when not antagonized by predators, become themselves a pest not only grazing on macroalgae, but finally also on corals and rock, and so eroding the total reef base (Glynn, 1984; Bellwood et al., 2004). When these grazers die off or migrate, they leave barren substrate behind which may be the base for extensive algal growth due to their efficient resettlement capabilities compared to that of corals (Hughes, 1994; Gardner et al., 2003), especially when coral recruitment is low (Aronson et al., 2002). Coral reefs threatened by a combination of anthropogenic stressors, such as eutrophication together with overfishing and mechanical habitat destruction due to the use of explosives (McManus et al., 1997), are at particularly high risk of imminent phase shift (Rogers, 1990; Hughes, 1994; Bellwood et al., 2004).

Located in the vicinity of the coral triangle, which is recognized as the epicenter of coral reef biodiversity (Briggs, 2005; Hoeksema, 2007), Hainan features environmental settings considered optimal for reef growth. Shallow water depths, tropical temperatures and sufficient sunlight are considered to be main drivers in reef development and persistence (Kleypas et al., 1999) and are all given in the island's adjacent coast. However, the coral reefs of Hainan are yet poorly investigated. Descriptions from the 1950s focus on distribution and diversity of coral communities (Yu and Zou., 1996a,1996b), while later studies on coral diversity investigated anthropogenic effects (Yu and Zou. 1996a,1996b; Shi and Zhang., 2004). The findings raised concerns that the rapid economic growth and associated fishing, agriculture and aquaculture development had taken their toll, causing heavy eutrophication, pollution, and a demise of coral reefs in coastal waters. Reefs on the south coast of Hainan saw decreases in live coral cover from 60% in 1983, to 41.5% in 1998, and to 21.51% in 2002 (Yu and Zou, 1996a,1996b), one evidence that the foundation of the Sanya National Coral Reef Reserve in 1990 has not been a sufficient measure. During a reef and seagrass monitoring project in 2002 (Status of China Marine Ecology Report, 2002), coral, seagrass and fish species distribution, biomass and recruitment was assessed along the east coast of Hainan. The results revealed that live coral cover and coral recruitment, as well as coral reef associated fish and invertebrate density were very low, while macro-algal abundance, especially that of the brown algae *Sargassum* spp. was high (Hainan east coast coral reef and seagrass monitoring report, 2005). Therefore, further information on the status of Hainan's coral reefs and their potential threats is urgently needed to provide the base for a more sustainable coastal management. Here, we describe five coral reef ecosystems along the NE coast of Hainan and investigate the metabolic status of the massive coral *Porites lutea*, a wide-spread, abundant, and well-studied reef builder (Veron, 2000), to determine present reef condition and set a baseline for further studies in the area.

2. Material and methods

2.1. Assessment of study sites

In 2007 and 2008 field trips were conducted to the NE reef sites of Hainan (Fig. 1). Five reefs were sampled (from north to south): Tongguling, Dongjiao Yelin, Changqi, Qinggeand Tanmen. Representative photographs displaying typical site characteristics for each reef are given in Fig. 2. Due to constraints in time, logistics and sampling, rapid assessments of the status of each reef were carried out and documented photographically. In detail, the study sites were examined in terms of coral cover, macroalgal cover, remaining substrate cover, grazer abundance, and general conspicuous factors such as visibility, recruit abundance, fish abundance, and diversity. Herein, estimates were either performed by recording percentages or in categories (excellent, sound, fair, poor). All estimates were independently recorded by two or three divers swimming U-search patterns of 100 m × 10 m in size at speeds of $<1\ \mathrm{m\ s^{-1}}$ for 40 min. Records were subsequently collated and used if the estimate was congruent or if differences did not exceed 5%. An overview on differences between reef sites is given in Table 1. All fringing reefs along the NE-coast of Hainan are located in shallow waters (2–8 m) relatively close to shore (200–1000 m) and consist of a reef flat, crest and slope. The first inspection of the working areas revealed only fragmentary reefs with extensive overgrowth by macroalgae, coral rubble fields and only marginal live coral cover (often less than 1%). Higher and more diverse coral cover (up to 15%) was found along the reef crests where wave and surge action was strongest resulting in constant removal of sediments. Most (60%) of the living colonies were, however, small and partly affected by disease or mortality and often threatened by algal overgrowth or snail predation. By contrast, we documented a high abundance of crustose coralline algae and of fleshy macro-algae, the latter especially on the reef slopes, but almost a total lack of mobile marcofauna, especially of key functional groups of herbivorous and predatory fish or grazing echinoderms. Visibility was low (between 0.5 and 8 m) and coral rubble fields were generally covered with thick layers of sediment. A more detailed description of each site is given in the following:

Tongguling—The shallow reef flat of Tongguling (2–5 m) consisted of extensive coral rubble fields. The unsorted fragments suggest they originate from destructive bomb fishing, not storms, where the waxing and waning of waves result in well-sorted coral fragments (Dollar, 1982). The coral rubble was cemented together by encrusting algae, indicating that the destruction of the reef has not happened recently. Live coral cover was low (5–10%), but increased to 40% on the reef crest and diversity was highest compared to all other reefs observed. In the area of low cover, mainly small branching species could be observed, and diversity rose with increasing cover. Algae were present, but were less abundant than at other reef sites. Fish abundance was negligible and most individuals were juvenile.

Dongjiao Yelin—The coral reef of Dongjiao Yelin is likewise shallow (2–4 m) and close to shore (~400 m). The widespread coral rubble fields on the reef flat, likely originating from destructive fishing methods, were mainly covered and clotted by silt. Fleshy green algae were abundant, but large *Sargassum* spp. specimens dominated the area. Only few small individuals of massive coral colonies could be observed, many of them diseased, damaged or encroached by algae. Close to the reef crest, where currents were stronger and waves present, the framework of the original reef still remained intact in great parts and featured many recruits of mainly branching coral species. There were only few fish, even along the reef crest.

Changqi—The reef area of Changqi is further offshore (~800 m) and depth ranges from 4 to 8 m. The site seemed to be heavily fished as indicated by high amounts of fishing boats in the reef area and audible as well as visible reoccurring explosions. Few large (several meters in diameter) massive *Porites* colonies represented the main part of live coral cover sustaining the damaged reef framework. However, many of them were affected