Massive coral mortality following a large flood event.

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Abstract. In early 2011, heavy rain associated with a strong La-Niña caused extensive flooding in the Fitzroy catchment, central Queensland. More than 33 million mega-liters of water flowed from Fitzroy River between December 2010 and March 2011, creating an extensive freshwater plume within the southern Great Barrier Reef lagoon. During this period, we recorded high mortality of scleractinian corals on the reef at Great Keppel Island, located <50 km from the river mouth. In particular, there was 100% mortality among 60 tagged colonies of *Acropora millepora*. Prior to the flood event, annual per capita mortality among tagged colonies was very low (1.1%), whereby only 1 (out of 60 colonies) had died during 18-months of study. This study shows that while it is important to quantify rates of background mortality (in the absence of major disturbance events) among coral populations, periodic and acute disturbances are likely to have an over-riding influence on population dynamics. Clearly therefore, the persistence of coral populations will depend upon the future frequency and severity of these major disturbances.

Key words: Coral reef, Disturbance, Bleaching, Salinity

Introduction

Disturbances play an important role in the structure and dynamics of coral reef communities (Connell 1997, Hughes and Connell 1999). While moderate levels of disturbance make an important contribution to increasing biodiversity (Connell 1978), natural acute events (e.g., cyclones) have combined with chronic stressors (e.g., overfishing, pollution and eutrophication) to cause excessive disturbance and hence degradation of coral reef environments (Hughes et al. 2003). In particular, effects of climate change (ocean warming, acidification, sea level rise, and rainfall patterns) are compounding upon pre-existing disturbance regimes (Hughes et al. 2003) at a frequency that can limit the capacity of corals to recover between successive events. Low-salinity stress following high rainfall and severe cyclones adds to a large number of acute disturbances affecting coral reefs.

On the Great Barrier Reef plumes of reduced seawater salinity (as low as 28ppt) can persist for up to 7 weeks following major cyclones (van Woesik et al. 1995, Devlin et al. 1998, Berkelmans and Oliver 1999). Mass bleaching and coral mortality has been recorded during these flood events (van Woesik et al. 1995, van Woesik 1991). Moderate exposure (short exposure to very low salinities, or prolonged exposure to only slightly reduced salinity) can result in bleaching (Kerswell and Jones 2003). Corals may survive moderate exposure and eventually recover from such events (Jokiel et al. 1993). However, corals exposed to very low-salinity seawater first bleach and then die, leaving tissue-free skeletons that may be mistaken for live corals that have lost their symbiotic algae (Kerswell and Jones 2003). Rapid mortality, apparent as sloughing of tissues, is likely caused by excessive water absorption to redress internal salinity gradients, leading to tissue swelling and damage (van Woesik et al. 1995). Similarly in seaweeds, hypo-osmotic stress causes increases in cell volume and turgor, leading to cell rupture (Lobban & Harrison 1994).

This study documents effects of a major flooding event in the southern Great Barrier Reef, on tagged corals at the Keppel Islands. In early 2011, heavy rain associated with a strong La-Niña (with the highest recorded December South Oscillation Index since 1973 (+27.1)) caused extensive flooding in the Fitzroy catchment, central Queensland. More than 33 million mega-liters of water flowed from the Fitzroy River between December 2010 and March 2011, creating an extensive freshwater plume within the southern Great Barrier Reef. Unfortunately, we were unable to assess the immediate consequences of this flood event, although extensive coral bleaching was observed at the Keppel Islands in late January 2011

(A. Jones, Pers. Comm.). In this study the fate of coral colonies, some of which had been followed for nearly 2 years, was recorded in April 2011, 1-2 months after the peak flooding.

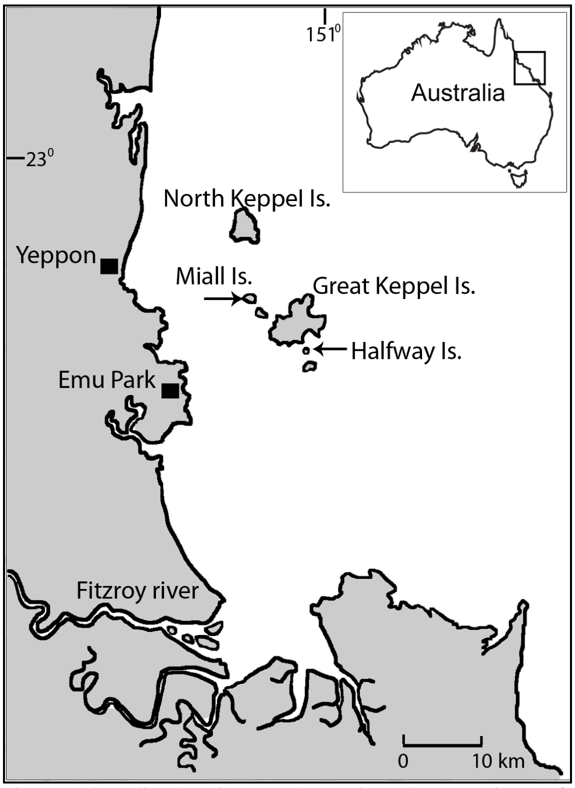

Figure 1: Sampling locations on the southern Great Barrier Reef. Arrows indicate approximate positions of specific sampling locations. at Miall Island and Halfway Island

Material and Methods

This research was conducted at in the Keppel Island group, located on the inshore Great Barrier Reef (GBR), within 50km of the mouth of the Fitzroy River (Fig. 1). Sampling was conducted at two islands (Miall Island and Halfway Island), located on the northwest and south sides of Great Keppel Island, respectively (Fig. 1). At each location, thirty colonies of seemingly healthy *Acropora millepora* species were identified and tagged in April 2009. All colonies were located on the shallow reef flat, less than 5 meters below the Highest Astronomical Tide.

Subsequent sampling trips were conducted from April 2009 to April 2011 to monitor the long-term fate of individually tagged colonies. Whenever one of the coral died, a new colony was tagged to ensure that proportional mortality recorded during each sample interval was based on 30 colonies per locations. During the first 12 months, four trips were conducted at 3-month intervals, with remaining trips conducted a 6-month intervals (Table 1). During sampling, every coral was photographed, and the condition (alive or completely dead) of the colony was recorded. The maximum diameter of each coral was also recorded (to the nearest cm), both to quantify growth rates, as well as to test for size selectivity in rates of mortality. The maximum diameter of colonies ranged from 10.7 to 42.0cm, with a mean of 23.5 (±0.9SE).

Results and Discussion

Of the 60 colonies of *A. millepora* colonies that were originally tagged, all survived throughout the first 12 months of sampling, up until April 2010 (Table 1). Between April 2010 and October 2010, a single coral colony had died at Halfway Island. The cause of this mortality is unknown, but may reflect normal, low rates of background mortality that are part of the natural dynamic and turnover in coral populations (Wakeford et al. 2008). The loss of this single coral colony after 18 months corresponds with an average annual mortality of 1.1%, which is well below the annual mortality recorded during 22 years of monitoring at Lizard Island in the northern GBR (Wakeford et al. 2008). Even in years without any major disturbances (cyclones, bleaching or outbreaks of crown-of-thorns starfish), Wakeford et al. (2008) reported 8-30% mortality among different species of *Acropora*, with a mean of 9% (±1.5 SE) for *A. milleopora*. Few studies have documented rates of coral mortality in the absence of major disturbance events, though this is critical in understanding the potential for recovery and resilience of coral populations subject to increasing incidence of major disturbances. Differences in our estimates of per capita mortality relative to Wakeford et al. (2008) also suggest that there may be marked differences in rates of background mortality among reefs, habitats, and/ or geographic locations.

In contrast to low levels of mortality (1.1%) recorded throughout the first 18 months of this study, 100% of colonies were found dead in April 2011 (Table 1). It seems likely that this comprehensive mortality was associated with the major flood event that occurred in early 2011. A strong La-Nina event (with the highest recorded December South Oscillation Index since 1973 (+27.1)) in the Pacific Ocean caused heavy rainfall, flooding the Fitzroy catchment (Bureau of Meteorology 2011). More than 15 million mega-liters of water flowed past The Gap station of Fitzroy River in January alone, contributing to a total flow of 33 million mega-liters recorded throughout the 2010-11 wet season. This was the biggest flood event since 1991, and the third biggest flood on record (Bureau of Meteorology 2011). The resulting flood-plume extended >300km north to Mackay, evident from MODIS satellite imagery on 25th January 2011 (Brodie et al. 2012). Presently there is limited data on salinity gradients with distance from the river mouth, or with depth.

Sampling time	Coral Mortality	
	Miall Island	Halfway Island
Apr-09	0	0
Jul-09	0	0
Oct-09	0	0
Dec-09	0	0
Apr-10	0	0
Oct-10	0	1
Apr-11	30	30

Table 1: Number of dead *Acropora millepora* recorded during each sampling trip.

Extensive bleaching was observed at Great Keppel Islands in the weeks following the flooding (A. Jones Pers. Comm.). All colonies of *A. millepora* that occurred in <2m water depth were dead in late January 2011, whereas colonies in deeper water were bleached but not yet dead (A. Jones Pers. Comm.). In addition to comprehensive mortality of tagged corals, we were unable to locate any live colonies of *A. millepora* on the reefs around the sampling locations in April 2011. Rather, all corals in the vicinity of our tagged corals were dead (Fig. 2). We also conducted visual surveys (20 minutes haphazard with snorkel and SCUBA covering approximately 1.5 hectares of reef in total) at a total of 8 other sites on Miall Island, Middle Island, Halfway Island, Humpy Island, and Great Keppel Island, during April 2011 to search for any surviving *A. millepora*. However, no living *A. millepora* species was found above 5 m, and not more than 10 colonies of *Porites* spp. were see alive. It was not possible to survey below 5 m because of poor visibility. These observations suggest that reduced salinity possibly exacerbated by high sediment loads killed most coral colonies over a large spatial scale on shallow reefs in the Keppel Islands.

Disturbances that result in high mortality are a natural feature of coral reef dynamics and may in fact be a promoting force of the biodiversity associated with these ecosystems at moderate frequencies and intensities (Connell 1997, Hughes and Connell 1999). In the face of increasing frequent local and global impacts, the future of coral reefs as we know them, strongly relate to the rates and potential for recovery of corals. It is, therefore, important that we understand how long it takes for coral assemblages to recover after disturbance through re-growth, of survivors and/or new recruits. Following the most recent major bleaching event in the Keppel Islands (in 2006), recovery of corals was exceptionally fast.

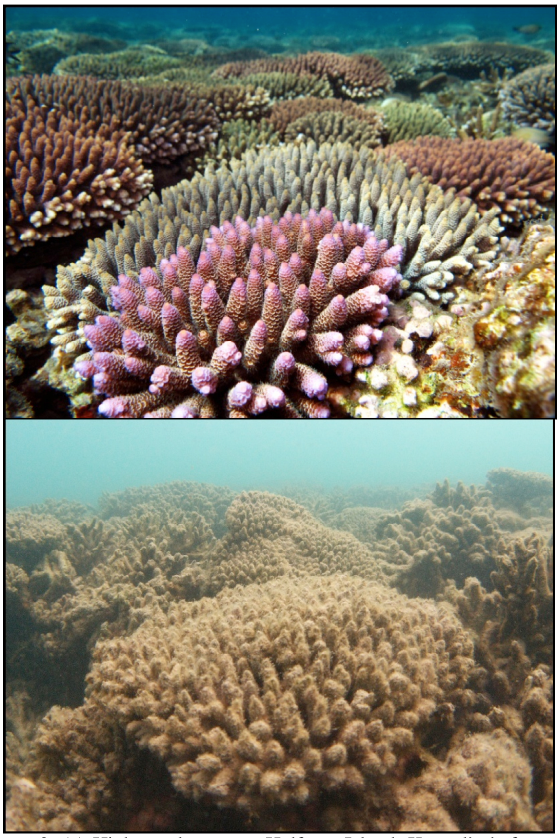

Figure 2: (a) High coral cover at Halfway Island, Keppel's before the fresh-water bleaching; (b) 100% mortality was observed on all reef flats after the 2011 flooding.

Despite marked reductions in coral cover (>60%) and a corresponding increase in macroalgae, coral cover returned to pre-bleaching levels within 12 months (Diaz-Pulido et al. 2009). Based on these findings we might expect that coral assemblages on inshore reefs in the southern GBR are resilient to periodic disturbances. It is important, however, to consider the detailed impacts of the disturbance before rates of recovery can be predicted. For example, a large difference between the recent flooding mortality and the bleaching studied by Diaz-Pulido et al. (2009) is that all corals studied in April 2011 were completely dead. Recovery following the 2006 bleaching was largely facilitated by re-growth from remnant patches of live tissue at the base of most colonies, and the apparent loss of live coral was exaggerated by rapid increases in the cover of macroalgae (Diaz-Pulido et al. 2009). In contrast, we failed to find any remnant patches of live tissue on any of the 60 tagged colonies, and the seascape was dominated by dead, but intact corals, comprehensively covered with turf algae and associated sediment (Fig. 2b). Recovery of coral assemblages following comprehensive mortality relies on settlement and subsequent growth of new recruits

(Connell 1997), which will take years to decades, rather than months, and only if are no other major disturbances in the intervening period.

Coral assemblages in the Keppel Islands may appear more resilient than many other reefs, given the rapid growth of colonies (Tan et al. unpublished data; Diaz-Pulido et al. 2009) and low rates of background mortality (Table 1). However, the overwhelming dominance of *Acropora spp.* in these coral assemblages (Jones et al. 2011) makes them particularly susceptible to acute disturbances such as thermal anomalies (Baird and Marshall 2002) and cyclones and other physical disturbances (Madin and Connolly 2006), which generally affect *Acropora* more than other taxa (Berumen and Pratchett 2006). Both of these types of disturbance are projected to increase in frequency and/or intensity with global warming (Emanuel 2005; Donner 2009). Consequently, there is an urgent need to understand the relative significance of acute disturbance in the demography of coral species.

Acknowledgement
This research was supported by the ARC Centre of Excellence for Coral Reef Studies and Malaysia Ministry of Higher Education. We thank the Department of Environment and Resource Management for providing data for the Fitzroy River flood, A. Jones for Figure 2b and R. Berkelmans and A. Jones for comment on the manuscript.

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