Summer growth rates of corals at Lord Howe Island, Australia

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Abstract. Spatial, temporal and taxonomic differences in coral growth play an important role in the ecology and dynamics of coral reef ecosystems, affecting reef productivity, heterogeneity, and growth. Moreover, climate change poses an increasing risk to the future status of coral reefs with increasing ocean temperature and acidification causing reductions in growth of reef-building corals, if not survivorship. The purpose of this study was to measure the growth rate of six scleractinian corals, *Acropora yongei*, *Isopora cuneata*, *Pocillopora damicornis*, *Porites heronensis, Seriatopora hystrix* and *Stylophora pistillata,* at Lord Howe Island, Australia's southernmost coral reef environment, during the 2010-11 summer growing season. Measurements were taken to compare growth rates of corals from other sub-tropical locations, and greatly increase understanding of the effects of climate change on coral growth. At high latitude locations (subtropical reefs), coral growth is currently limited by the cool winter temperatures and climate related increases in ocean temperature may extend the summer growing period. Conversely, aragonite saturation declines with increasing latitude and climate-induced ocean acidification may further reduce the capacity for growth of calcifying organisms at the latitudinal limits of reef growth. Coral growth (specifically, linear extension) was measured at North Bay and Horseshoe Reef using i) Alizarin staining, and ii) changes in length of individually tagged branches. *Acropora* displayed at least two fold higher growth rates, significantly greater than other genera, whereas *Pocillopora* had the lowest growth rate. There was limited evidence of recent increases in growth rates of corals, rather growth rates of *Pocillopora* were much lower than expected. While very preliminary, these findings suggest that declining aragonite saturation, which will have most pronounced effects on high latitude reefs, are already offsetting any positive effect of increasing temperature.

Key words: Coral reef, Linear extension, Subtropics

Introduction

Climate change poses a significant and increasing risk to the distribution and survival of reef-building corals (Hoegh-Guldberg 1999), as many reef-building corals are extremely sensitive to sustained and ongoing increases in ocean temperatures (Hughes et al. 2003), as well as emerging effects of ocean acidification (Hoegh-Guldberg et al. 2007). Most corals are adapted to local environmental temperature (Hughes et al. 2003), and typically bleach and die if the local temperature exceeds the normal summer maxima by >1°C for 3 to 4 weeks (Hoegh-Guldberg 1999). Even if climate change does not significantly and directly alter the survivorship of reef building corals, there are likely to be significant consequences for individual growth rates (e.g., Cooper et al. 2008, Cantin et al. 2010). Cooper et al. (2008) for example showed that calcification, a proxy for growth, of massive *Porites* on Australia's Great Barrier Reef has declined by 21% from 1988 to 2003.

Recent declines in growth rates have also been demonstrated for branching corals, including *Pocillopora* from Pacific Panama (Manzello 2010) and *Acropora palmata* in the Caribbean (Bak et al. 2009). However, both these studies were conducted in locations where aragonite saturation is expected to limit coral growth, rather than temperature. Branching corals are generally considered to be much more susceptible to extreme temperatures (Marshall and Baird 2000) and ocean acidification (Fabricius et al. 2011), compared to massive coral species. However, measuring specific responses of branching corals to changing environmental conditions requires direct measurements because annual density bands, used to hindcast growth rates of massive corals, are rarely present (Gladfelter 1982). For branching corals, any effects of declining calcification on linear extension may also be offset by reductions in skeletal density (Lough 2008).

Changes in environmental conditions may have both positive and negative effects on coral growth. At some subtropical reefs, coral growth is currently limited by cool winter temperatures (Harriott 1999, Crossland 1981), whereby coral growth is negligible

during winter months. Consequently, increasing temperatures due to climate change may greatly extend the growing period, leading to overall to increases in annual growth rates (Cooper et al. 2012). However, positive effects of increasing temperature at subtropical locations may be offset by declines in carbonate saturation. Aragonite saturation declines with increasing latitude and climate-induced ocean acidification may further reduce the capacity for growth of calcifying organisms at the latitudinal limits of reef growth (Kleypas et al. 1999).

The aim of this study was to quantify summer growth rates for a range of scleractinian corals, especially, branching species, at Lord Howe Island. Lord Howe, located at 31.5°S, represents eastern Australia's southernmost coral reef formation (Harriott et al. 1995). Coral assemblages at this location are relatively depauperate, comprising approximately 83 species (Harriott et al. 1995).

Material and Methods
This study was conducted in December 2010 to March 2011 at Lord Howe Island, located 600 kilometres off the coast of New South Wales, Australia. Sampling for this study was conducted at North Bay (S31°31.273, E159°2.773) and Horseshoe Reef (S31°32.554, E159°3.704), located 1.5 kilometres apart within the extensive lagoon system that extends along the northwest coastline of Lord Howe Island. At each site, a 20 metre long permanent transect was established at 4 m depth, marked using 50 cm stainless steel stakes hammered into the reef.

Study species
Growth rates were measured for 6 species of scleractinian corals: *Acropora spp., Porites heronensis, Pocillopora damicornis, Isopora cuneata, Stylophora pistillata* and *Seriatopora hystrix.* Measurements of growth rates for *Acropora* spp. were mostly conducted using large and distinctive colonies of *Acropora yongei*, but given the relatively low number of colonies of clear taxonomic identity and atypical morphologies of *Acropora* at Lord Howe Island (A. Baird, unpublished data), a wide range of different *Acropora* species of uncertain species identity were sampled.

Coral growth rates were quantified by comparing changes in size over the 15 week summer growth period, from December 12-15, 2010 to March 24-31, 2011. Linear extension of corals was measured using two methods: i) directly measuring changes in the length of branches or columns from a fixed reference point, marked using plastic cable ties; ii) recording the extent of new skeletal growth by staining corals with Alizarin-red, following Lamberts (1978) and Harriott (1999). A total of three branches per colony

were selected and tagged using small plastic cable ties. Cable ties were secured 10-30 mm from the tip of each branch, then recording the exact distance from the top of the tie buckle to the branch tip on each sampling occasion (Fig. 1). Corals selected for staining (Table 1), were completely enclosed within a plastic bag, and exposed to 10 mg/L of Alizarin Red. Given limited success in staining corals on subtropical reefs (e.g., Harriott 1999) the exposure time was increased from 3-4 hours (which is commonly used at tropical locations) to 7-8 hours, accounting for slow rates of calcification. After 15 weeks, stained corals were sacrificed to measure the linear extent of new growth above well-defined staining bands. Linear extension was measured on 20-34 branches per colony (Table 1), depending on colony size.

Figure 1: Direct measurements of linear extension were obtained by recording the distance from the cable tie to the branch tip, using callipers, on each sampling occasion.

Table 1: Number of colonies (C) and branches (Br) used for direct tagged linear extension, and stained linear extension.

	Direct		Stained	
	C	Br	C	Br
Acropora	28	67	4	110
Isopora	22	65	4	78
Pocillopora	23	67	3	224
Porites	24	70	4	89
Seriatopora	21	49	4	175
Stylophora	20	51	4	135

Statistical Analysis
Variation in linear extension was analysed using a mixed-model analysis of variance (ANOVA), testing for differences among locations, among genera, and among colonies (within genera). Due to the limited number of colonies stained using Alizarin red, analyses were conducted to first confirm that there was no significant ($p > 0.05$) effect of location, and then data from both locations was pooled to test for differences among genera, and among colonies

(within genera). Tukey's' HSD post hoc tests were used to identify specific differences among genera, following ANOVA.

Results

Direct Tagging

Linear extension, measured as change in length for individually tagged branches (or columns), was quantified for 394 branches, on 138 colonies from 6 genera. Of the 394 branches that were tagged in December 2010, 93.7% (369/394) were alive and growing in March 2011. Estimates of linear extension obtained using direct tagging were consistent between sites for all genera except *Acropora* where the linear extension at Horseshoe Reef was 14.76 ± 1.45 mm (mean ± SE) and North Bay was 18.53 ± 2.47 mm. The linear extension varied significantly within and among coral genera (Table 2). *Acropora* had the greatest mean linear extension (16.62 ± 1.43 mm) (Fig. 2). The slowest growing coral was *Pocillopora* with a branch mean linear extension of 2.15 ± 0.27 mm.

Table 2: Mixed-model ANOVA to test for differences in linear extension of corals measured using direct measurements of branch length, at Lord Howe Island.

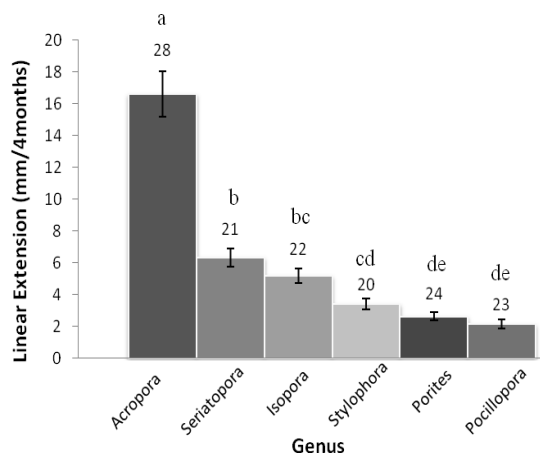| Effect	SS	df	F	p
Location	24.11	1	1.14	0.29
Genus	9492.09	5	89.74	0.00
Location*Genus	389.46	5	3.68	0.00
Colony(Genus)	5286.32	71	3.52	0.00
Error	6050.34	286		

Figure 2: The direct linear extension of coral genera over the summer growth period (early Dec-end Mar). Each coral colony had 3 cable ties secured over the summer for the direct measurement. The number of colonies measured (N) and Tukey's grouping is provided. Data was combined from Horseshoe Reef and North Bay.

Alizarin Stain

Alizarin red was incorporated relatively uniformly into the skeleton across all areas of coral colonies that were stained at Lord Howe Island, providing a clear reference to measure subsequent coral growth. Estimates of linear extension from stained corals were significantly different within and among genera (Table 3). *Acropora* had the fastest mean growth rate (13.59 ± 0.59 mm) (Fig. 3). Again, *Pocillopora* had the least growth (4.81 ± 0.12 mm).

Table 3: Nested ANOVA for Alizarin stained to test for differences in linear extension of corals, measured following staining with Alizarin Red, at Lord Howe Island. Data was pooled across study locations (North Bay and Horseshoe Bay) to increase sample size and statistical power.

Effect	SS	Df	F	p
Genus	4793.28	5	109.64	0.00
Colony(Genus)	772.15	17	5.19	0.00
Error	6872.82	786		

The extension rates recorded from colonies stained using Alizarin red were generally lower than estimates obtained using direct tagging. For *Acropora*, for example, average linear extension recorded using direct tagging was 4.15 mm/month, compared to 3.40 mm/month for corals stained using Alizarin Red. The taxonomic differences in growth rates of corals were much better resolved using direct tagging. However, the approximate rankings, where *Acropora* has the fastest growth rates, *Pocillopora* the slowest, and limited differences between *Seriatopora*, *Isopora*, *Stylophora* and *Porites* were consistent for both techniques.
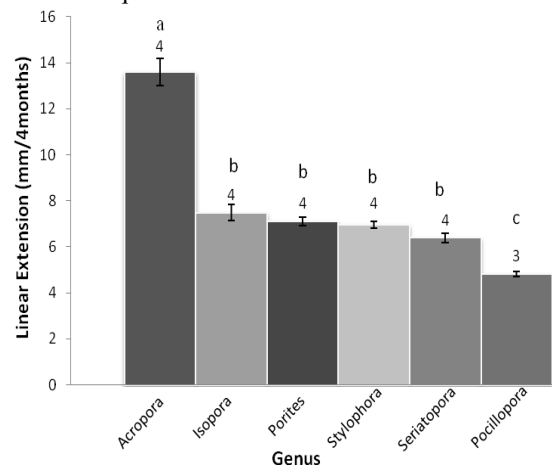

Figure 3: The linear extension (mm) determined over the summer growth period at Lord Howe Island using Alizarin Red stain. All branches from each colony or portion of colony collected were measured to the nearest millimeter. The number of colonies measured (N) is provided along with Tukey's grouping

Discussion

Growth rates of scleractinian corals have a fundamental influence on all aspects of their biology and ecology (Connell 1973). It is also known that growth rates are inherently variable among different corals species, partly in accordance with differences in gross morphology, skeletal structure and polyp size (Hall and Hughes 1996). In general, branching corals are characterised by their rapid linear extension (Buddemeier and Kinzie 1976), though growth is sometimes moderated by the need to increase skeletal density to withstand hydrodynamic forces (Hughes 1987). In contrast, massive corals, especially massive *Porites* tend to grow much more slowly (Connell 1973). At Lord Howe Island, there were marked inter-specific differences in summertime growth rates, but these differences were not related to colony morphology. Both *Isopora cuneata* and *Porites heronensis*, which have columnar growth forms, had higher growth rates compared to *Pocillopora damicornis*, but grew more slowly when compared to *Acropora.*

Growth rates of *Acropora* corals recorded at Lord Howe Island (4.15-3.40 mm/month) in the present study, were much greater than have been documented for comparable subtropical locations, such as the Solitary Islands. Harriott (1999) quantified summertime growth rates of 0.46 mm/month for *A. cytherea* and 0.80 mm/month for *A. valida* at the Solitary Islands, in the mid 1990's using Alizarin stain. These differences may be partly attributable to the specific species of coral considered, whereby most *Acropora* colonies at Lord Howe were staghorn corals (mostly, *A. yongei*), which are known to have faster growth rates compared to tabular (*A. cytherea*) or corymbose (*A. valida*) corals. However, the sea surface temperature (SST) in the current study ranged from 23.35-25.4°C (http://data.aims.gov.au/), remarkably higher than the SST (20.5°C) recorded by Harriott (1999) at the Solitary Islands, which may be contributing to greater growth rates. However, the summer growth rate determined at Lord Howe Island is still much lower compared to tropical locations, such as Davies Reef on the Great Barrier Reef where the summer SST reaches 30°C. At Davies Reef the linear extension of staghorn *Acropora* was determined using Alizarin stain to be 6.66 mm/month at 5 metres depth (Oliver et al. 1983), 38% greater than the current study.

Aside from *Acropora*, *Pocillopora* is often considered to be among the fastest growing scleractinian corals (Buddemeier and Kinzie 1976). At Lord Howe Island, however, *P. damicornis* was the slowest growing of all corals studied. The current rate 0.54-1.20 mm/month (direct and staining methods, respectively) is comparable to growth rates of *P. damicornis* determined using Alizarin stain at Rottnest Island, Western Australia (0.75-1.25 mm/month); these figures were extrapolated from six months growth during Dec 1988 to June 1989 (Ward 1995). Our estimates of linear extension for *P. damicornis* were 29-68% lower when compared to the summer growth rates at the Solitary Islands determined using Alizarin stain in 1994/1995 (Harriott 1999). Possibly *P. damicornis* is allocating most of its energy for reproduction in the summer accounting for the reduced summer growth. It remains to be seen whether these corals continue to grow over winter at Lord Howe, but if not, the current growth rates is also much lower than total annual growth estimates for this species at Lord Howe in the mid 1990's (Harriott 1999).

Understanding how climate change will affect corals in subtropical locations requires a better understanding of temperature performance of corals plus experimental studies to test whether corals in subtropical locations have higher or lower sensitivity to increasing temperatures compared to their tropical counterparts. Temperature-growth response curves are well established for scleractinian corals (Buddemeier and Kinzie 1976). As greater skeletal elongation with increasing temperature is observed seasonally in the subtropics (Crossland 1981), rising global temperatures could support greater subtropical coral growth rates. However, elevated temperatures have been shown to have a greater affect on branching species, such as *Acropora* and *Pocillopora* (Marshall and Baird 2000), which is a cause of concern for high latitude reef corals where their upper thermal limits are lower than for their low latitude counterparts (Cook et al. 1990).

Growth rates of corals in sub-tropical locations are clearly limited by temperature (Kleypas et al. 1999), but any increases in temperature will not necessarily lead to increased growth. In the south Pacific, the ocean is undersaturated with aragonite (Kleypas et al. 1999), and aragonite saturation is expected to continue to decrease throughout this century (Orr et al. 2005). Projected changes in the seawater chemistry, specifically ocean acidification, are expected to lead to major contractions in the geographical extent of areas that are amenable to calcification (Hoegh-Guldberg et al. 2007). The first and worst affected areas are likely to be locations at the current geographic limits of coral growth, especially high latitude reefs. The slow and seemingly reduced growth of *P. damicornis* at Lord Howe Island may reflect initial effects of ocean acidification, though it is unclear why such affects would disproportionately affect *Pocillopora* and not *Acropora* (Langdon and Atkinson 2005).

This study increases knowledge of coral growth and interspecific variation in responses of corals to environmental change at high latitude reefs. An explicit resolution of recent changes in growth rates for common coral genera will be apparent when the annual sampling is completed, allowing direct comparison to annual estimates of coral growth by Harriott (1999). However, our data suggest that subtropical reefs are not necessarily going to provide adequate refuges from sustained and ongoing climate change, as these environments are likely to be the first and worst affected due to climate change, especially given ocean acidification is likely to constrain coral growth regardless of increases in sea surface temperature.

Acknowledgement

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