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SHORT COMMUNICATION

GROWTH MODELLING INDICATES HURRICANES AND SEVERE STORMS
ARE LINKED TO LOW CORAL RECRUITMENT IN THE CARIBBEAN

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1 ABSTRACT

2 This study set out to test the hypothesis that hurricanes and tropical storms limit the
3 recruitment and subsequent survival of massive non-branching corals on the barrier
4 reef off the coast of Belize in the Gulf of Honduras. Overall, the surface areas of 523
5 individual coral specimens were measured, and recruitment dates were then modelled.
6 There was no significant difference in coral cover or coral biodiversity between any of
7 the sites studied ($p>0.1$). There were significant differences in non-branching coral
8 recruitment in years when hurricanes impacted the area ($p<0.05$) compared with years
9 when no hurricanes impacted the area. There were significantly more non-branching
10 massive corals recruited in non-hurricane years (mean 7.7) than in hurricane years
11 (mean 3.8; $p=0.011$). When years with tropical storms are added to the years with
12 hurricanes, there was significantly lower coral recruitment (mean 4.7) relative to non-
13 storm or hurricane years (mean 7.4; $p=0.019$). These results show that hurricanes and
14 severe storms limited the recruitment and survival of massive non-branching corals of
15 the Mesoamerican barrier reef and on patch reefs near the Belize coast in the
16 Caribbean, and suggests that marine park managers may need to assist coral
17 recruitment in years where there are hurricanes or severe storms.

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2 1. INTRODUCTION

3 There is observational evidence for an increase of intense tropical cyclone
4 activity in the North Atlantic since about 1970, correlated with increases of tropical
5 sea surface temperatures (IPCC, 2007). Based on a range of models, it is likely that
6 future tropical cyclones (typhoons and hurricanes) will become more intense, with
7 larger peak wind speeds and more heavy precipitation associated with ongoing
8 increases of tropical SSTs (IPCC, 2007). An increasing amount of evidence is now
9 accumulating for a direct relationship between global warming and increasing
10 hurricane intensity as well as increasing hurricane frequency (Elsner et al., 2006a, b).
11 Global warming produces significant increases in the frequency of high sea surface
12 temperatures (SSTs) (Hoegh-Guldberg, 1999), and hurricane winds are strengthened
13 by warm surface waters. Our recent work on the effects of temperature on coral
14 growth on fringing reefs off the coast of Curaçao suggest that a 30-day averaged
15 maximum daily temperature can explain about 3% of the variability in the time-
16 dependent growth rate (Crabbe et al., 2008), suggesting that during the measurement
17 period, temperatures rose to higher than optimum temperatures for growth, thus
18 inhibiting coral growth, but were not sufficiently high to cause bleaching of this
19 species. This result points to the very narrow temperature range for coral growth, and
20 to how sensitive corals are to fluctuations in temperature, particularly to rates of
21 temperature change (Dodge and Lang, 1983; Dodge and Brass, 1984; Dunbar et al.,
22 1994; Crabbe, 2007).

23 Maintaining coral reef populations in the face of large scale degradation and
24 phase-shifts on reefs depends critically on recruitment (Hughes, 1994; Hughes and
25 Tanner, 2000; Coles and Brown, 2007), and the present study set out to test the
26 hypothesis that hurricanes and tropical storms limit the recruitment and subsequent
27 survival of massive non-branching corals. We have shown previously, using

1 modeling based on growth rate data, that this was the case on the fringing reefs of the
2 north coast of Jamaica near Discovery Bay (Crabbe et al., 2002; 2004), and now
3 wished to test that hypothesis on the barrier reef off the coast of Belize, in the
4 Sapodilla Cayes Marine Reserve, and in the patch reefs in the Port Honduras Marine
5 Reserve, near to Punta Gorda Town in Belize, in the Gulf of Honduras.

6

7 2. METHODS

8 SITES

9 There are two major coral reef areas in Southern Belize, the Sapodilla Cayes Marine
10 Reserve (SCMR, a World Heritage Site), and the Port Honduras Marine Reserve
11 (PHMR). The SCMR is a 125 km² reserve and has had a collaborative agreement with
12 the Belize Fisheries Department and the Toledo Association for sustainable Tourism
13 (TASTE) to manage the area since its declaration in 1996. The PHMR is a 414 km²
14 reserve, and has been managed by the Toledo Institute for Development and
15 Environment (TIDE) since its declaration in January 2000. Sample sites were
16 selected from both reserves (Fig. 1), and GPS coordinates (given in the legend to Fig.
17 1) were determined using a hand-held GPS receiver. Basic water quality
18 measurements were made at one PHMR site (South Snake Caye) in August 2006,
19 with results as follows: salinity – 34.14.ppt; temperature – 30.1 °C; dissolved oxygen-
20 81.1% saturation; pH – 8.48; Turbidity- 0.1 Nephelometric Turbidity Units (NTU);
21 phosphates – 0.22 mg/l; nitrates- 0.4 mg/l; chlorophyll – 0.1 mg.l. This work was
22 conducted in July and August 2006, and in August 2007.

23

24 SAMPLING

25 Coral cover was determined at each site using the line intercept transect method, over
26 haphazardly allocated 10m transects at each site above (Osborne and Oxley, 1977).
27 Surface areas of live non-branching corals were determined at the sites as described

1 previously using SCUBA (Crabbe et al., 2002; 2004; Crabbe and Smith, 2003; 2005).
2 74% of the samples came from SCMR sites, 26% from PHMR sites. Calculations on
3 the samples showed no significant differences in recruitment between the sites in the
4 SCMR, and likewise for sites in the PHMR. Depth of samples was between 8-12 m, to
5 minimise variation in growth rates due to depth (Huston, 1985). To increase accuracy,
6 surface areas rather than diameters of live non-branching corals were measured.
7 Sampling was over as wide a range of sizes as possible, but no corals ≤ 5 mm in
8 diameter were measured. Colonies that were close together (<5 cm) or touching were
9 avoided to minimise age discontinuities through fission and altered growth rates
10 (Hughes and Jackson, 1980; Elahi and Edmunds, 2007), and we took pains to measure
11 corals that were widely spaced apart. Overall, 523 individual coral specimens were
12 measured. These included the major species measured (numbers of individuals in
13 brackets): *Agaricia agaricites* (23), *Agaricia tenuifolia* (39), *Colpophyllia natans* (49),
14 *Dichocoenia stokesii* (17), *Diploria labyrinthiformis* (24), *Diploria strigosa* (48),
15 *Montastrea annularis* (10), *Montastrea cavernosa* (61), *Montastrea faveolata* (26),
16 *Montastrea franksei* (32), *Meandrina meandrites* (10), *Mycetophyllia spp.* (23),
17 *Porites astreoides* (58), *Porites porites* (21), *Siderastrea siderea* (37), *Stephanocoenia*
18 *intersepta* (13).
19 The year of an individual's recruitment was calculated from a knowledge of the
20 growth rate (e.g. 3.25 mm/yr for *Porites astreoides*, 3 mm/yr for *Siderastrea siderea*)
21 (Dodge and Vaisnys, 1975; Hubbard and Scaturo, 1985; Huston, 1985; Carricart-
22 Ganivet et al., 2000), taken from sites in the Caribbean at similar depths and visibility
23 to those encountered here, the majority from Huston (1985). For example, a *Porites*
24 *astreoides* colony of measured elliptical surface area 51.8 cm² was estimated to have
25 recruited (and survived) 23 years ago. We modelled changes to the growth rates
26 similar to those encountered at different sites and similar depths from the references
27 above, and in none of the colonies studied did this amount to a change in estimated

1 recruitment date of < 2 years over 50 years. One or two-factor ANOVA was used to
2 compare coral data among sites; \pm error values represent standard deviations of the
3 data.

4

5 DATA ON STORMS AND HURRICANES IMPACTING BELIZE

6 Data on storm severity as it impacted the SCMR AND PHMR areas was
7 obtained from UNISYS (<http://weather.unisys.com/hurricane/atlantic/>) the NOAA
8 hurricane site (<http://www.nhc.noaa.gov/pastall.shtml>) and the Belize tropical storm
9 site: <http://www.hurricanecity.com/city/belize.htm>.

10

11 3. RESULTS

12 There was no significant difference in coral cover or coral biodiversity between
13 the sites in the SCMR (24% \pm 10% coral cover overall), or in the PHMR (17% \pm
14 7% coral cover overall), or between the PHMR and SCMR ($p>0.1$), although there
15 were no *Acropora palmata* branching colonies in the PHMR sites.

16 Fig. 2a shows the estimated recruitment dates for all 523 non-branching corals at
17 the SCMR and PHMR sites. Solid arrows show the years of hurricanes which
18 impacted the area, with their names (the hurricane in 1931 had no name); dotted
19 line arrows show the years where tropical storms impacted the area. Fig 2b shows
20 that there are significant differences in non-branching coral recruitment in years
21 when hurricanes impacted the area ($p<0.005$ for PHMR, $p<0.05$ for SCMR)
22 compared with years when no hurricanes impacted the area. Overall, for both the
23 PHMR and the SCMR, there were significantly more non-branching massive
24 corals recruited in non-hurricane years (mean 7.7 \pm 5.6) than in hurricane years
25 (mean 3.8 \pm 2.9; $p=0.011$). When years with tropical storms are added to the
26 years with hurricanes, there was significantly lowered coral recruitment (mean 4.7
27 \pm 4.3) relative to non-storm or hurricane years (mean 7.4 \pm 5.7; $p=0.019$).

1

2 4. DISCUSSION

3

4 Multiple stressors, hurricanes and bleaching, have caused significant disturbances to
5 populations of coral recruits in Belize (Mumby, 1999). Hurricanes and tropical
6 storms cause major damage and delayed mortality to corals (Knowlton et al., 1981;
7 Done, 1999), as happened with hurricane Allen in 1980 to the fringing reefs off
8 Discovery Bay in Jamaica (Woodley et al., 1981). Alteration of substratum by storms
9 reduces recruitment rates, as does the pre-emption of space by other corals or
10 macroalgae (Connell, 1997; Connell et al., 1997). Ecosystem thresholds have been
11 modelled to identify targets for reef restoration (Mumby et al., 2007), and it appears
12 that grazing, for example by parrotfish, is critical to reef resilience and restoration in
13 the face of continuing hurricane intensity (Bythell et al., 2000; Mumby et al., 2007).
14 While we have not measured coral recruitment directly in this study, our modelling
15 work has shown that hurricanes and severe storms have limited the recruitment and
16 survival of massive non-branching corals on the fringing reefs near Discovery Bay
17 (Crabbe et al., 2002; 2004), and here we show that the same is true for non-branching
18 corals of the Mesoamerican barrier reef in the Sapodilla Cayes, and for corals on
19 patch reefs in the Port Honduras Marine Reserve near the Belize coast in the Gulf of
20 Honduras. While occasional storms can increase the survivorship of branching
21 *Acropora palmata* colonies (Lirman, 2003), storm-induced decrease in reef rugosity
22 can limit the settlement of coral planulae, as survival is greater in the shade or under
23 surfaces (Birkland, 1977). While some coral communities may adapt to chronic
24 stressors, for example sedimentation, over long periods of time (Flood et al., 2005),
25 acute stresses such as those induced by high wave energy during storms could reduce
26 the reproductive output of corals (Ward, 1995; Baird and Marshall, 2002), and thus
27 lower coral recruitment. Storms and hurricanes can influence sedimentation and

1 turbidity, which themselves have significant effects on coral growth (Gilmour, 1999;
2 Crabbe and Carlin, 2007). Increased freshwater inputs from storms reduces salinity,
3 which in turn increases pre-and post-settlement mortality, changed larval behaviour
4 and substrate choice upon settlement (Vermeij et al., 2006). What our work suggests
5 is that marine park managers may need to assist coral recruitment and settlement in
6 years where there are hurricanes or severe storms, by setting up coral nurseries
7 (Forsman et al., 2006) and / or natural or artificial high rugosity substrate on the reef.

8

9 Acknowledgements

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11 Burton Shank (Conservation International) for essential help with the GPS
12 coordinates. We also thank Dennis and Sandra Garbutt for their vital organisational
13 support during the project, and the anonymous referees for suggesting improvements
14 to the manuscript.

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ACCEPTED MANUSCRIPT

1 Legends to Figures.

2

3 Fig. 1. Coral reef sites in Southern Belize. The Sapodilla Cayes Marine Reserve
4 (SCMR), in dark grey shading to the left of the figure, comprises the southern end of
5 the MesoAmerican Barrier Reef, and includes Seal Cay, Frank's Cay, Nicholas Cay,
6 Hunting Cay and Lime Cay, where the SCMR sites were located. The Port Honduras
7 Marine Reserve (PHMR), in dark grey shading to the right of the figure, is close to the
8 coast near Punta Gorda Town. The PHMR sites were c. 1-3 km SW of South Snake
9 Cay. SCMR sites were: Mantas garden (N16° 09.614' W88° 14.823'), Franks I (N16°
10 08.173' W88 20.113'), Franks II (N16° 08.188' W88° 20.087'), Seal Cay (N16° 10.537'
11 W88° 19.960'), Nicholas Cay (N16° 06.661' W88° 15.430'), and Protected I site (N16°
12 06.769' W88° 16.589'); PHMR sites were: South Snake Cay (N16° 10.550' W88°
13 33.815'), and Barracuda Bank (N16° 09.679' W88° 34.647'). North is to the top of the
14 page.

15

16 Fig. 2. Estimated recruitment dates for non-branching corals.

17 a, estimated recruitment dates for all 523 non-branching corals at the SCMR and
18 PHMR sites. Solid arrows show the years of hurricanes which impacted the area,
19 with their names (the hurricane in 1931 had no name); dotted line arrows show the
20 years where tropical storms impacted the area.

21 b, Histogram showing significant differences in non-branching coral recruitment in
22 years when hurricanes impacted the area ($p < 0.005$ for PHMR, $p < 0.05$ for SCMR)
23 than in years when no hurricanes impacted the area.

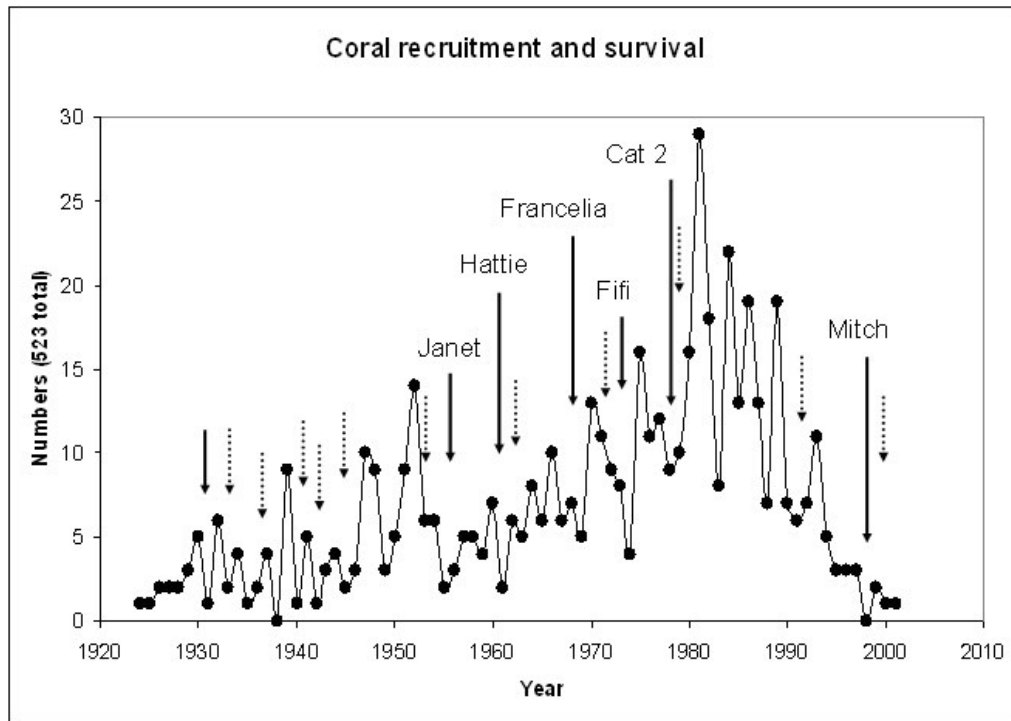
1 Figure 1



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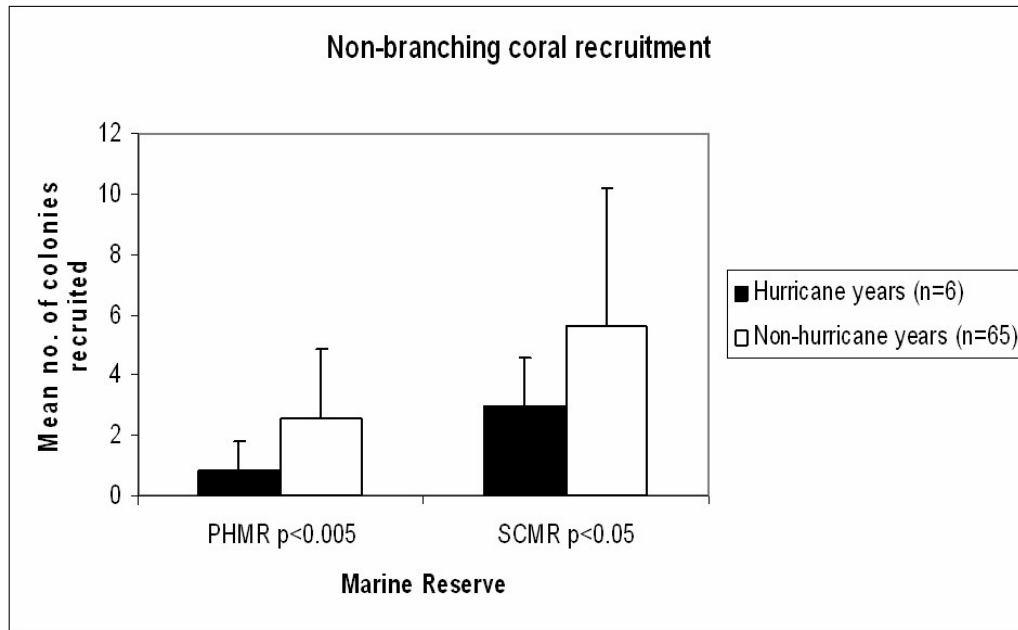
1 Figure 2a



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1 Figure2b



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