

APPENDIX S2: SUPPLEMENTARY TABLES

Table S1. Coral demographic parameters of ReefMod-GBR.

	Arborescent (staghorn) acroporids	Plating acroporids	Corymbose / small branching acroporids	Pocilloporids / non- acroporid corymbose	Small massive / submassive / encrusting	Large massive
Representative coral taxa	<i>Acropora muricata, Acropora nobilis, Acropora robusta</i>	<i>Acropora hyacinthus, Acropora cytherea</i>	<i>Acropora millepora, Acropora humilis</i>	<i>Stylophora pistillata, Pocillopora damicornis, Seriatopora hystrix</i>	<i>Lobophylliidae, faviids, Goniastrea</i>	<i>Porites lutea, Porites lobata</i>
Radial extension of adult colonies (cm yr ⁻¹)	4.4 ^[a]	4.4 ^[b]	3.0 ^[c]	2.4 ^[d]	0.8 ^[e]	1.2 ^[f]
Radial extension of juveniles (cm yr ⁻¹) ^[g]	1.0	1.0	1.0	1.0	1.0	1.0
Fecundity parameter <i>a</i> ^[h]	1.03	1.03	1.69	-1.20	0.86	0.86
Fecundity parameter <i>b</i> ^[h]	1.28	1.28	1.05	2.27	1.21	1.21
Minimum size of full fecundity (cm ²) ^[h]	123	123	134	31	38	38
Maximum settler density α (m ⁻²) ^[i]	0.5	2.5	2.5	1.5	1.5	1.5
Larval density for $\alpha/2$ (m ⁻²) ^[i]	5,000	5,000	5,000	5,000	5,000	5,000
Juvenile mortality (yr ⁻¹) ^[i]	0.2	0.2	0.2	0.2	0.2	0.2
Whole-colony mortality of small (< 250 cm ²) corals (yr ⁻¹) ^[k]	0.004	0.190	0.172	0.226	0.040	0.040
Whole-colony mortality of large (\geq 250 cm ²) corals (yr ⁻¹) ^[k]	0.002	0.098	0.088	0.116	0.020	0.020
Relative sensitivity to partial mortality ^[l]	2.0	0.4	1.4	1.8	1.0	1.0
Relative sensitivity to	1.4	1.6	1.5	1.1	0.6	0.5

	Arborescent (staghorn) acroporids	Plating acroporids	Corymbose / small branching acroporids	Pocilloporids / non- acroporid corymbose	Small massive / submassive / encrusting	Large massive
cyclones ^[m]						
Relative sensitivity to bleaching ^[m]	1.5	1.6	1.4	1.7	0.25	0.25

^a Horizontal projection of branch extension $8.2 \text{ cm.yr}^{-1} \times \cos(45^\circ)$: Crossland 1981, Oliver et al. 1983, Dennison and Barnes 1988, Simpson 1988, Harriott 1998, Anderson et al. 2017.

^b Stimson 1985, Jokiel and Tyler 1992.

^c Stimson 1985, Jokiel and Tyler 1992, Clark and Edwards 1995, Morgan and Kench 2012.

^d Crossland 1981, Oliver 1985, Stimson 1985, Simpson 1988, Jokiel and Tyler 1992, Harriott 1999, Anderson et al. 2012.

^e Knutson et al. 1972, Buddemeier 1974, Highsmith 1979, Babcock 1991, Clark and Edwards 1995.

^f Knutson et al. 1972, Buddemeier 1974, Highsmith 1979, Barnes and Lough 1989, Jokiel and Tyler 1992, Clark and Edwards 1995, Morgan and Kench 2012.

^g Extension rate of Pocilloporid and Acroporid juveniles (1 mm diameter) on a reef slope (≤ 5 m depth) at Heron Island (Doropoulos et al. 2015).

^h Hall and Hughes 1996.

ⁱ Determined by calibration against observations of coral juvenile densities (Traçon et al. 2013) and rates of coral recovery (Emslie et al. 2008); assumes the juvenile taxonomic composition observed by Traçon et al. (2013): *Acropora* ~40-60%, *Pocillopora* ~5-15%, *Porites* ~15-30%, others ~10-20%.

^j Mortality of juveniles (≤ 5 cm maximum diameter) of *Acropora* spp. on a reef slope (≤ 5 m depth) at Heron Island (Doropoulos et al. 2015).

^k Chronic (background) whole-colony mortality rates based on *Porites astreoides* in the Caribbean (Bythell et al. 1993, Mumby and Dytham 2006) further adjusted to each coral group following calibration with Pacific corals (Ortiz et al. 2014).

^l Coefficients to adjust the extent of tissue lost (partial mortality) estimated from colony size (empirical relationship based on 6 Caribbean species, Meesters et al. 1997, detailed in Appendix S1). Coefficients were determined by calibration with Pacific corals (Ortiz et al. 2014).

^m Based on taxa-specific responses to storms of different categories assessed using the AIMS LTMP transect surveys database: cover change of each taxa relative to total cover change after cyclone exposure. Multiplied by 6 after calibration with the observed changes in coral cover.

ⁿ Based on (Hughes et al. 2018), taking as baseline an average bleaching mortality of ~20% across taxa.

Table S2. Literature data on mortality rates from manipulative in situ experiments (Keesing and Lucas 1992, Sweatman 1995, Okaji 1996, Keesing et al. 1996, 2018) and monitoring of CoTS cohorts (Zann et al. 1987, 1990). Daily mortality rates were estimated from the reported surviving fractions and the duration of each study. Median ages are the representative age of the surviving fractions, extrapolated from initial age and study duration (except for Sweatman 1995), and subsequently used as point estimates for the empirical model of mortality at age.

Location	Initial age (months)	Initial size range or mean (mm)	Study duration (days)	Median age (months)	Surviving fraction (%)	Daily mortality (%.d ⁻¹)	Reference
Suva Reef, Fiji	8–23	NA	487	16	0.7 ^c	1.01	¹ (Zann et al. 1987)
GBR mid-shelf, various habitats	22–34	NA	365	28.0	23.7	0.39	² (Doherty and Davidson 1988)
Suva Reef, Fiji	22–28	NA	182	25	27.5 ^d	0.71	³ (Zann et al. 1990)
Davies Reef (12-15m)	1	0.6–1.7 (1.0)	5.75	1.1	62	7.98	⁴ (Keesing and Halford 1992)
Davies Reef (12-15m)	4	0.7–4.7 (2.8)	13	4.2	85	1.24	⁴ (Keesing and Halford 1992)
Davies Reef (12-15m)	7	1.4–6.0 ^a (4.9)	16	7.3	94	0.54	⁴ (Keesing and Halford 1992)
Davies Reef back reef (3-9m)	NA	15–79	35	~14.6 ^b	NA	0.41	⁵ (Sweatman 1995)
Davies Reef (12-15m)	1	1.0–1.6	9	1.1	NA	7.80	⁶ (Keesing et al. 1996)
Davies Reef leeward slope (10m)	0.3	0.6	49	1.1	1	8.97	⁷ (Okaji 1996)
Davies Reef leeward slope (10m)	0.3	0.7	37	0.9	14.7	5.05	⁷ (Okaji 1996)
Davies Reef leeward slope (10m)	2	1.2	57	2.9	22.6	2.57	⁷ (Okaji 1996)
Davies Reef leeward slope (10m)	3	3.2	92	4.5	38.7	2.40	⁷ (Okaji 1996)
Davies Reef (10m)	3	3	17	3.3	60.4	2.92	⁸ (Keesing et al. 2018)
Davies Reef (10m)	15	13	17	15.3	82.5	1.13	⁸ (Keesing et al. 2018)

^a 7mo-old starfish stunted due to lack of food (expected size at this age is 12-28mm, Zann et al. 1990).

^b Median age extrapolated from size-at-age data (Zann et al. 1987).

^c Mass mortality due to disease.

^d Uncertain estimates of abundance and aggregative CoTS distribution.

Table S3. Coral cover changes across the GBR and shelf from 2008 to 2020 (13 years).

	Initial coral cover (%cover)	Absolute change (%cover)	Proportional change
GBR			
Cross-shelf	28.8	-9.6	-33%
Inner-shelf	33.4	-19.0	-57%
Mid-shelf	27.5	-5.2	-19%
Outer-shelf	27.4	-11.2	-41%
Northern GBR			
Cross-shelf	28.3	-15.2	-54%
Inner-shelf	31.7	-20.2	-64%
Mid-shelf	28.4	-15.1	-53%
Outer-shelf	24.8	-10.4	-42%
Central GBR			
Cross-shelf	22.9	-2.9	-13%
Inner-shelf	30.4	-15.9	-52%
Mid-shelf	21.5	+1.7	+8%
Outer-shelf	21.7	-7.6	-35%
Southern GBR			
Cross-shelf	33.1	-8.6	-26%
Inner-shelf	36.6	-19.0	-52%
Mid-shelf	30.9	-2.7	-9%
Outer-shelf	36.1	-15.5	-43%

Table S4. Impacts of significant cyclones during 2008–2020 as absolute (% cover) and proportional (in parenthesis) coral cover loss (ie, relative to pre-cyclone total coral cover) averaged by region. Cyclone impacts result from reef-level predictions cyclone severity (Saffir-Simpson category) and simulated coral community composition.

Cyclone	GBR	North	Central	South
Hamish (2009)	-9.9 (-30%)		-5.0 (-19%)	-22.5 (-65%)
Olga (2010)	-0.4 (-2%)		-1.0 (-4%)	-0.2 (-2%)
Yasi (2011)	-1.1 (-6%)		-4.4 (-23%)	
Tim (2013)	-2.3 (-10%)	-0.8 (-2%)	-3.0 (-15%)	-3.0 (-14%)
Ita/Dylan (2014)	-2.2 (-8%)	-2.6 (-8%)	-3.9 (-16%)	-0.7 (-3.5%)
Nathan/Marcia (2015)	-3.7 (-14%)	-3.0 (-10%)		-6.8 (-26%)
Debbie (2017)	-2.6 (-9%)		-8.1 (-24%)	-1.5 (-8%)
Iris (2018)	-0.6 (-3%)		-1.8 (-9%)	-0.4 (-3%)
Trevor (2019)	-0.4 (-3%)	-0.8 (-5%)		

Table S5. Variance component analysis of coral recovery. Relative contribution of simulated environmental variables to the variations of coral community growth (g) measured as the percent deviance explained by separate GLMs with a single predictor, and by a global GLM with all predictors included. Code for environmental variables: *Coral* – coral cover; *Sand* – cover of sand; *Rubble* – cover of loose coral rubble; $WQ_{repro}/WQ_{recruit}/WQ_{juv}$ – sediment-driven potential of coral reproduction/recruit survival/juvenile; $Supply_{prop}$ – relative proportion of external larval supply; $Supply_{num}$ – number of external supply links. Final regression model (*R* software pseudo-syntax): $g + 2 = \text{poly}(Coral, 2) : (\text{asin}(WQ_{juv}) + \text{asin}(WQ_{recruit}) + \log(1+Rubble) + Sand + \text{sqrt}(Supply_{num}) + \text{sqrt}(Supply_{prop}) + \text{asin}(WQ_{repro}))$, family = Gamma(link = log).

GLMs	% deviance explained (all reefs)	% deviance explained (inshore reefs)
<i>Coral</i>	25.0	5.7
<i>Sand</i>	3.2	4.2
$WQ_{recruit}$	0.7	3.8
WQ_{juv}	0.5	2.5
WQ_{repro}	0.5	2.1
$Supply_{prop}$	0.1	0.2
$Supply_{num}$	0.0	0.0
<i>Rubble</i>	0.0	0.2
<i>Coral</i> : ($WQ_{juv} + WQ_{recruit} + Rubble + Sand + Supply_{num}$ + $Supply_{prop} + WQ_{repro}$)	35.6	18.4

Table S6. Distribution of coral health status predicted in 2020 (post-bleaching) among reefs of the entire GBR ($n=3,806$ reefs) and in each region region (North: $n=1,200$; Central: $n=958$; South: $n=1,648$).

Reef status	GBR	North	Central	South
Critical (<10%)	22%	41%	21%	9%
Poor (10–20%)	41%	44%	46%	38%
Moderate (20–30%)	18%	9%	18%	24%
Healthy (>30%)	19%	6%	15%	29%

REFERENCES

- Anderson, K. D., N. E. Cantin, S. F. Heron, C. Pisapia, and M. S. Pratchett. 2017. Variation in growth rates of branching corals along Australia's Great Barrier Reef. *Scientific reports* 7:1–13.
- Anderson, K., M. Pratchett, and A. Baird. 2012. Summer growth rates of corals at Lord Howe Island, Australia.
- Babcock, R. C. 1991. Comparative demography of three species of scleractinian corals using age- and size-dependent classifications. *Ecological Monographs* 61:225–244.
- Barnes, D. J., and J. M. Lough. 1989. The nature of skeletal density banding in scleractinian corals: fine banding and seasonal patterns. *Journal of Experimental Marine Biology and Ecology* 126:119–134.
- Buddemeier, R. W. 1974. Environmental controls over annual and lunar monthly cycles in hermatypic coral calcification. Pages 259–267 *Proc 2nd Int Coral Reef Symp.*
- Bythell, J. C., E. H. Gladfelter, and M. Bythell. 1993. Chronic and catastrophic natural mortality of three common Caribbean reef corals. *Coral Reefs* 12:143–152.
- Clark, S., and A. J. Edwards. 1995. Coral transplantation as an aid to reef rehabilitation: evaluation of a case study in the Maldives. *Coral reefs* 14:201–213.
- Crossland, C. J. 1981. Seasonal growth of *Acropora* cf. *formosa* and *Pocillopora damicornis* on a high latitude reef (Houtman Abrolhos, Western Australia). *Proceedings of the Fourth International Coral Reef Symposium*:663–667.
- Dennison, W. C., and D. J. Barnes. 1988. Effect of water motion on coral photosynthesis and calcification. *Journal of Experimental Marine Biology and Ecology* 115:67–77.
- Doherty, P. P., and J. J. Davidson. 1988. Monitoring the distribution and abundance of juvenile *Acanthaster planci* in the central Great Barrier Reef. Page *Proceedings of the 6th International Coral Reef Symposium, Townsville, Australia 8-12 August 1988*-pages: 2: 131-136.
- Doropoulos, C., S. Ward, G. Roff, M. González-Rivero, and P. J. Mumby. 2015. Linking demographic processes of juvenile corals to benthic recovery trajectories in two common reef habitats. *PLoS ONE* 10:e0128535.
- Emslie, M., A. Cheal, H. Sweatman, and S. Delean. 2008. Recovery from disturbance of coral and reef fish communities on the Great Barrier Reef, Australia. *Marine Ecology Progress Series* 371:177–190.
- Hall, V., and T. Hughes. 1996. Reproductive strategies of modular organisms: comparative studies of reef-building corals. *Ecology* 77:950–963.
- Harriott, V. J. 1998. Growth of the staghorn coral *Acropora formosa* at Houtman Abrolhos, Western Australia. *Marine Biology* 132:319–325.
- Harriott, V. J. 1999. Coral growth in subtropical eastern Australia. *Coral Reefs* 18:281–291.
- Highsmith, R. C. 1979. Coral growth rates and environmental control of density banding. *Journal of Experimental Marine Biology and Ecology* 37:105–125.
- Hughes, T. P., J. T. Kerry, A. H. Baird, S. R. Connolly, A. Dietzel, C. M. Eakin, S. F. Heron, A. S.

- Hoey, M. O. Hoogenboom, G. Liu, and others. 2018. Global warming transforms coral reef assemblages. *Nature* 556:492.
- Jokiel, P. L., and W. A. Tyler. 1992. Distribution of stony corals in Johnston Atoll lagoon. Pages 683–692 *Proceedings of the Seventh International Coral Reef Symposium*.
- Keesing, J. K., and A. R. Halford. 1992. Importance of postsettlement processes for the population dynamics of *Acanthaster planci* (L.). *Marine and Freshwater Research* 43:635–651.
- Keesing, J. K., A. R. Halford, and K. C. Hall. 2018. Mortality rates of small juvenile crown-of-thorns starfish *Acanthaster planci* on the Great Barrier Reef: implications for population size and larval settlement thresholds for outbreaks. *Marine Ecology Progress Series* 597:179–190.
- Keesing, J. K., W. L. Wiedermeyer, K. Okaji, A. R. Halford, K. C. Hall, and C. M. Cartwright. 1996. Mortality rates of juvenile starfish *Acanthaster planci* and *Nardoa* spp measured on the Great Barrier Reef, Australia and in Okinawa, Japan. *Oceanologica acta* 19:441–448.
- Knutson, D. W., R. W. Buddemeier, and S. V. Smith. 1972. Coral chronometers: seasonal growth bands in reef corals. *Science* 177:270–272.
- Meesters, E. H., I. Wesseling, and R. P. Bak. 1997. Coral colony tissue damage in six species of reef-building corals: partial mortality in relation with depth and surface area. *Journal of Sea Research* 37:131–144.
- Morgan, K. M., and P. S. Kench. 2012. Skeletal extension and calcification of reef-building corals in the central Indian Ocean. *Marine environmental research* 81:78–82.
- Mumby, P. J., and C. Dytham. 2006. Metapopulation dynamics of hard corals. Pages 157–203 *Marine metapopulations*. Elsevier.
- Okaji, K. 1996. Feeding ecology in the early life stages of the crown-of-thorns starfish, *Acanthaster planci* (L.). PhD thesis, James Cook University, Australia.
- Oliver, J. 1985. An evaluation of the biological and economic aspects of commercial coral collecting in the Great Barrier Reef Region. Report of the Great Barrier Reef Marine Park Authority, Townsville, Australia 106.
- Oliver, J. K., B. E. Chalker, and W. C. Dunlap. 1983. Bathymetric adaptations of reef-building corals at Davies Reef, Great Barrier Reef, Australia. I. Long-term growth responses of *Acropora formosa* (Dana 1846). *Journal of Experimental Marine Biology and Ecology* 73:11–35.
- Ortiz, J. C., Y.-M. Bozec, N. H. Wolff, C. Doropoulos, and P. J. Mumby. 2014. Global disparity in the ecological benefits of reducing carbon emissions for coral reefs. *Nature Climate Change* 4:1090.
- Simpson, C. J. 1988. Ecology of Scleractinian corals in the Dampier Archipelago. Western Australia Technical Series. Environmental Protection Authority, Perth.
- Stimson, J. 1985. The effect of shading by the table coral *Acropora hyacinthus* on understory corals. *Ecology* 66:40–53.
- Sweatman, H. P. A. 1995. A field study of fish predation on juvenile crown-of-thorns starfish. *Coral Reefs* 14:47–53.
- Trapon, M. L., M. S. Pratchett, and A. S. Hoey. 2013. Spatial variation in abundance, size and

orientation of juvenile corals related to the biomass of parrotfishes on the Great Barrier Reef, Australia. PLoS ONE 8:e57788.

Zann, L., J. Brodie, C. Berryman, and M. Naqasima. 1987. Recruitment, ecology, growth and behavior of juvenile *Acanthaster planci* (L.) (Echinodermata: Asteroidea). *Bulletin of Marine Science* 41:561–575.

Zann, L., J. Brodie, and V. Vuki. 1990. History and dynamics of the crown-of-thorns starfish *Acanthaster planci* (L.) in the Suva area, Fiji. *Coral Reefs* 9:135–144.