communications
earth & environment

MATTERS ARISING

https://doi.org/10.1038/s43247-022-00363-3 OPEN

Global predictions of coral reef dissolution in the Anthropocene

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ARISING FROM K. Davis et al. *Communications Earth & Environment* https://doi.org/10.1038/s43247-021-00168-w (2021)

Coral reef frameworks are constructed by calcifying organisms and are highly sensitive to ocean acidification. Shifting baselines in seawater chemistry have already had measurable impacts on net ecosystem calcification (G_{net}) on coral reefs[1], and projections of ocean acidification portray a poor future for reefs in the Anthropocene[2]. While experimental approaches have revealed much about this trajectory, we lack a clear understanding of: i) the drivers and predictors of net calcification at ecosystem scales, and ii) accurate predictions of when ecosystem calcification will reach net dissolution in the 21st century.

Through a meta-analysis approach, the recent study in Communications Earth & Environment by Davis et al.[3] provides important insights into ecosystem-scale calcification on coral reefs. Based upon 53 publications spanning 36 coral reef sites around the world, the study provides a more nuanced understanding of the global drivers of G_{net}. Cover of reef calcifiers (predominantly corals) and depth are key predictors of global ecosystem calcification, with evidence of seasonality and wave action as additional factors influencing G_{net}[3]. The meta-analysis outlines important knowledge gaps and research needs and highlights the limited data available for assessing changes in ecosystem calcification at the same reefs through time.

Under future projections, ocean acidification is expected to shift coral reefs from a state of net calcification to net dissolution through reductions in pH and aragonite saturation states (Ω_a)[4,5]. The exact timing of this is unclear, in part due to methodological differences, but estimates of when coral reefs will cross a tipping point to net dissolution vary substantially from 2031 to 2082[6], 2070[7], and 2060 to 2080[4]. Through the compilation of G_{net} from a subset of sites with repeated measurements (6 of the 36 available coral reefs; $n = 29$ of the available 116 surveys), Davis et al.[3] extrapolate linear predictions of G_{net} decline (1975–2017) to conclude that average global net-zero calcification will occur around the year 2054, based on a decline in G_{net} of $4.3 \pm 1.9\%\ yr^{-1}$.

Extrapolating estimates of G_{net} into the 21st century based upon the available historical data is complex. We identify four issues with this approach:

1. **Declines in G_{net} are modelled as a linear function**. The model assumes that declines in G_{net} are linear in nature, but relationships between Ω_{ar} and G_{net} are inherently nonlinear from the level of organismal differences in carbonate mineralogy[8] to ecosystem-level interactions with water flux, light, and temperature[9,10]. Increases in ocean temperature, be it spatial (e.g., depth, latitudinal) and/or temporal (e.g., diel, seasonal, inter-annual), interact to accelerate G_{net}. The ability of modest levels of warming to enhance G_{net} may at least in part buffer the impacts of ocean acidification on calcification rates[2], thereby delaying the transition to net dissolution. However, marine heatwaves and persistent ocean warming will have serious consequences for G_{net}, as will amplifying storms, cyclones and crown-of-thorns starfish outbreaks. Yet, local increases in (or recovery of) coral cover can rapidly increase G_{net} over a matter of years[11], further highlighting i) the nonlinearity in the environmental drivers of G_{net} and ii) the inherent complexity in accounting for ecosystem-scale feedbacks in future predictions of G_{net}.
2. **Extrapolation of limited local studies to global trends**. By modelling the linear decline in repeatedly-surveyed sites over time, Davis et al.[3] expect average global net-zero calcification around 2054. While this result is predicted at global scales, the underlying data represents just six Pacific reefs, of which three are from the Great Barrier Reef, Australia (Fig. 1). Given the global footprint of coral reefs (Fig. 1), predictions of global decline from this dataset are inherently limited in scale. When grouped by season (to account for the effect of temperature on G_{net}), the majority of sites are represented by just two data points (Table 1). Within locations, linear declines in G_{net} are mostly nonsignificant, except for Lizard Island, which is represented by the greatest sample size and is parallel to declines in coral cover (Fig. 1, Supplementary Code, see Code Availability Statement). The simple linear analysis is further complicated by environmental variability among seasons and wave exposure (Fig. 1). Predictions of declines in G_{net} based upon the limited available data mask local-scale variability, and the lack of repeated measures data within seasons hinders accurate extrapolation to global trends.
3. **Interacting environmental drivers of G_{net}**. While calcifier cover, temperature, season, depth and wave exposure can substantially alter measures of G_{net} (Fig. 2 in[3]), these drivers are considered as additive effects in Davis et al.[3] and are not included in modelling future predictions of G_{net} (likely due to the limited number of studies with repeated measures).

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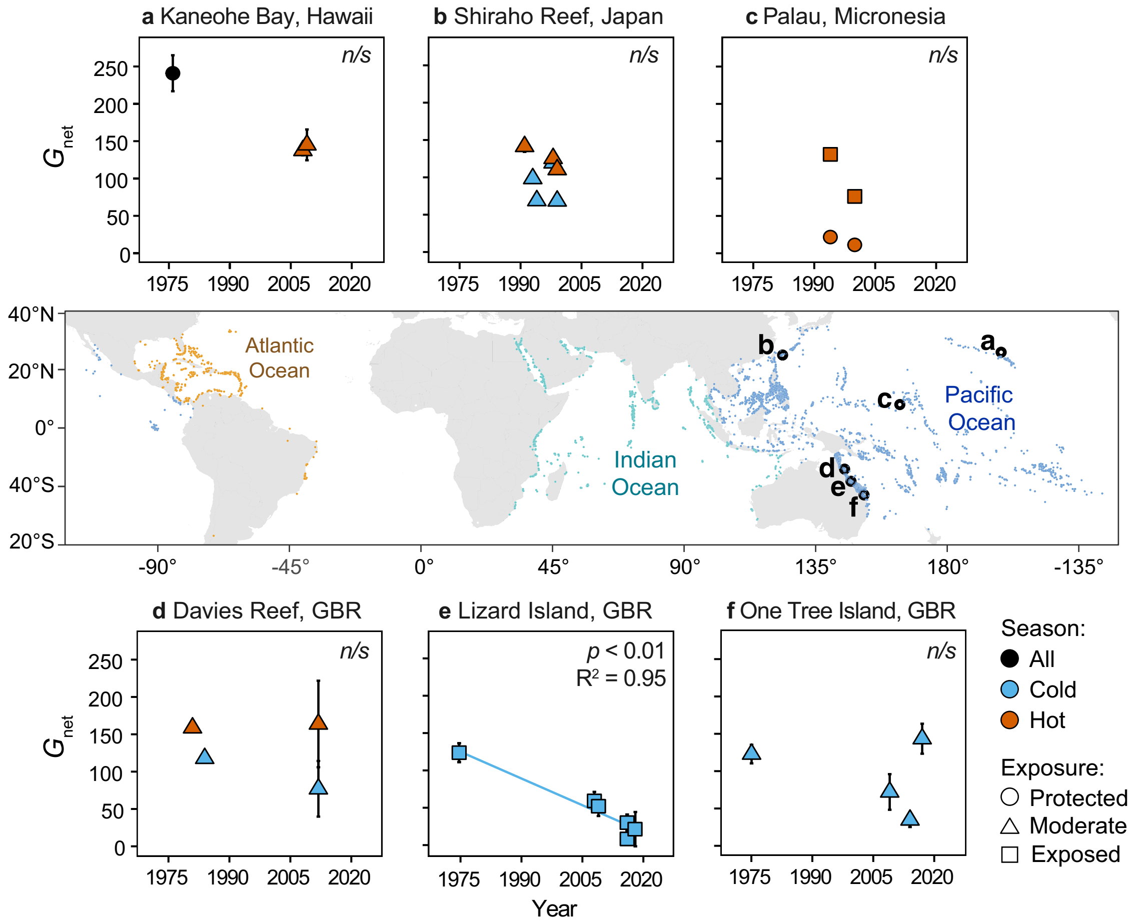

Fig. 1 Global changes in coral reef ecosystem calcification (G_{net}) over time. Trends in the subset of repeated measures surveys ($n = 29$) used by Davis, et al.[3] to predict global declines in G_{net} (mmol m^{-2} d^{-1}). Data separated by location (**a**–**f**) and season. Studies are placed in the context of the global footprint of coral reefs where colours denote the three main biogeographic regions: Pacific, Indian, and Atlantic Oceans.

Table 1 Breakdown of repeated measures surveys ($n = 29$) used by Davis, et al.[3] to project global declines in G_{net} when accounting for the season and seasonal bins (H hot, C cold, A all, GBR Great Barrier Reef).

Location	All	Summer	Autumn	Spring	Winter	Seasonal bin	*n*
Kaneohe Bay Hawaii	1					A	1
		2				H	2
Shiraho Reef, Japan				3	1	C	4
			3			H	3
Palau (reef flat)		1	1			H	2
(lagoon)		1	1			H	2
Lizard Island, GBR				6		C	6
		1				H	1
Davies Reef GBR					2	C	2
		2				H	2
One Tree Island, GBR				4		C	4

The linear model predicts global net dissolution in 2054, yet the confidence intervals surrounding this prediction are broad, and only 16% of the variance in the fixed effects can be explained by the temporal trajectory 'year' (Supplementary Code, see Code Availability Statement). Of the six sites used in the analysis, in only one location was G_{net} consistently quantified in the same season (Table 1). In Palau, measurements were quantified from two different habitats (reef flat and lagoon), each with a single summer and autumn survey (Table 1). Exposed reef flats and sheltered lagoons have distinct biogeochemistries and metabolisms[12], which confounds predictions of G_{net}. Data compiled within the same linear model without environmental variables treated as such (e.g., random effects) confound precise estimates of spatial and temporal change.

4. **Historical and contemporary patterns of G_{net}.** In assessing changes in biogeochemical processes on coral reefs, historical datasets represent a critical baseline with which

to assess recent change. The inclusion of an early study from Kaneohe Bay, Hawaii, complicates the analysis. Kinsey[13] noted his data were '*sparse and somewhat erratic*', that values of G_{net} were not weighted across seasons, and that values were over-represented by sampling in September when near-maximum metabolic rates occur (see footnote Table 38). Thus, the value of G_{net} of 241 mmol m^{-2} d^{-1} in 1976 (Fig. 1a) from Kinsey[13], which was used to benchmark a 40–43% decline in G_{net} between 1976 and 2009, is likely to be an overestimate. While historical datasets can be paired with contemporary studies at the scale of individual reefs, exact locations within reefs also vary. For example, historical measurements at Davies Reef in 1981 were conducted on the reef flat ~60 m from the windward margin[14], whereas contemporary measurements were conducted on the protected (lagoonal) side of the reef flat[15], some 300 m from the windward margin. Similarly, while the four studies ($n = 7$ surveys) from Lizard Island, Great Barrier Reef (1975–2019), were conducted on the same reef flat, they were situated > 1 km apart[16,17]. Spatial and temporal differences in environmental parameters (tides, depth, waves) and benthic structure (coral cover, seasonal algal blooms) confound paired measurements of G_{net} between historical and contemporary studies, and further complicate accurate predictions.

While meta-analysis of global datasets can yield important insights into the global drivers of coral reef ecosystem calcification, we reason that they are inherently limited in their capacity to accurately predict future states. The key conclusion of Davis et al.[3] is that we can expect to observe net-zero calcification in coral reefs around 2054, yet the 95% confidence interval from their model places tipping point this anywhere between 2030 and somewhere beyond 2150 (Supplementary Code, see Code Availability Statement). Rationalising that net dissolution will occur "around 2054" overlooks this high degree of variability and uncertainty. Given the points raised above, we agree with the conclusions of an earlier study by Davis et al.[11] in that '…*the predictive capabilities of ecosystem metabolism studies may be constrained by using the available short-term datasets to represent long-term calcification trends*'.

In light of the future predicted shifts in ocean chemistry[2], global predictions of coral reef dissolution are increasingly important. Given the environmental complexities and heterogeneity of coral reefs, the magnitude of declines in G_{net} will inherently be variable, non-linear and hard to predict. Regardless, the meta-analysis by Davis et al.[3] provides important insight into the future of G_{net} on coral reefs, including that i) reef slopes are likely to be more impacted than reef flats due to increased G_{net} at depth and extreme diel fluctuations in shallow water, and ii) reefs that support high levels of calcifiers and sustained coral cover may buffer declines in G_{net} due to changes in aragonite saturation state.

From a media coverage and policy perspective, conclusions of net-zero calcification in coral reefs around 2054 are striking and high-impact[18]. We argue that highlighting the uncertainty surrounding such estimates is essential. In future projections, local buffers in ocean chemistry and climate refugia may enhance adaptive capacity to the negative impacts of ocean acidification in future decades[5,19,20], while recovery of coral communities can rapidly increase G_{net}[11]. Identifying bright spots where coral reef calcification may be sustained long into the 21st century can build optimism and action at the interface between science and policy[21], and sustain motivation for adopting emissions pathways that will ensure a future for coral reefs in the Anthropocene.

Data availability

The authors declare that the data are sourced from the original publication and its Supplementary Information Files (https://doi.org/10.1038/s43247-021-00168-w) with amendments documented within the available R code.

Code availability

The authors declare that the R code to replicate the analysis and figures of this, and the original study, have been made available at https://github.com/marine-ecologist/global-predictions-of-coral-reef-dissolution.

Received: 29 June 2021; Accepted: 17 January 2022;
Published online: 25 February 2022

References

1. Albright, R. et al. Reversal of ocean acidification enhances net coral reef calcification. *Nature* **531**, 362–365 (2016).
2. Pandolfi, J. M., Connolly, S. R., Marshall, D. J. & Cohen, A. L. Projecting coral reef futures under global warming and ocean acidification. *Science* **333**, 418–422 (2011).
3. Davis, K. L., Colefax, A. P., Tucker, J. P., Kelaher, B. P. & Santos, I. R. Global coral reef ecosystems exhibit declining calcification and increasing primary productivity. *Commun. Earth Environ.* **2**, 1–10 (2021).
4. Silverman, J., Lazar, B., Cao, L., Caldeira, K. & Erez, J. Coral reefs may start dissolving when atmospheric CO2 doubles. *Geophys. Res. Lett.* **36**, L05606 (2009).
5. Anthony, K. R. N., Kleypas, J. A. & Gattuso, J. P. Coral reefs modify their seawater carbon chemistry - implications for impacts of ocean acidification. *Global Change Biol.* **17**, 3655–3666 (2011).
6. Eyre, B. D. et al. Coral reefs will transition to net dissolving before end of century. *Science* **359**, 908–911 (2018).
7. Cantin, N. E., Cohen, A. L., Karnauskas, K. B., Tarrant, A. M. & McCorkle, D. C. Ocean warming slows coral growth in the central Red Sea. *Science* **329**, 322–325 (2010).
8. Ries, J. B., Ghazaleh, M. N., Connolly, B., Westfield, I. & Castillo, K. D. Impacts of seawater saturation state (Ω_A=0.4-4.6) and temperature (10, 25°C) on the dissolution kinetics of whole-shell biogenic carbonates. *Geochim. Cosmochim. Ac* **192**, 318–337 (2016).
9. Kornder, N. A., Riegl, B. M. & Figueiredo, J. Thresholds and drivers of coral calcification responses to climate change. *Global Change Biol.* **24**, 5084–5095 (2018).
10. Cyronak, T., Schulz, K. G. & Jokiel, P. L. The Omega myth: what really drives lower calcification rates in an acidifying ocean. *Ices J Mar Sci* **73**, 558–562 (2016).
11. Davis, K. L., McMahon, A., Kelaher, B., Shaw, E. & Santos, I. R. Fifty years of sporadic coral reef calcification estimates at One Tree Island, Great Barrier Reef: is it enough to imply long term trends? *Front Marine Sci* **6**, 00282 (2019).
12. Cyronak, T. et al. Taking the metabolic pulse of the world's coral reefs. *PLoS One* **13**, e0190872 (2018).
13. Kinsey, D. W. *Carbon turnover and accumulation by coral reefs*, (University of Hawaii, 1979).
14. Barnes, D. J. Profiling coral reef productivity and calcification using pH and oxygen electrodes. *J. Exp. Mar. Biol. Ecol.* **66**, 149–161 (1983).
15. Albright, R., Langdon, C. & Anthony, K. R. N. Dynamics of seawater carbonate chemistry, production, and calcification of a coral reef flat, central Great Barrier Reef. *Biogeosciences* **10**, 6747–6758 (2013).
16. Silverman, J. et al. Community calcification in Lizard Island, Great Barrier Reef: A 33 year perspective. *Geochim. Cosmochim. Ac* **144**, 72–81 (2014).
17. Pichon, M. & Morrissey, J. Benthic zonation and community structure of South Island Reef, Lizard Island (Great Barrier Reef). *B. Mar. Sci.* **31**, 581–593 (1981).
18. SCU. *Declining growth rates of global coral reef ecosystems*, Southern Cross University, June 2021. https://www.scu.edu.au/engage/news/latest-news/2021/declining-growth-rates-of-global-coral-reef-ecosystems.php (2021).
19. Andersson, A. J., Yeakel, K. L., Bates, N. R. & de Putron, S. J. Partial offsets in ocean acidification from changing coral reef biogeochemistry. *Nat. Clim. Change* **4**, 56–61 (2014).
20. Kapsenberg, L. & Cyronak, T. Ocean acidification refugia in variable environments. *Global Change Biol.* **25**, 3201–3214 (2019).
21. Cvitanovic, C. & Hobday, A. J. Building optimism at the environmental science-policy-practice interface through the study of bright spots. *Nat. Commun.* **9**, 1–5 (2018).

Author contributions
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Competing interests
The authors declare no competing interests.

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