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Supplementary Materials for

Impaired recovery of the Great Barrier Reef under cumulative stress

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Supplementary Materials:

Section S1. Exploration of potential confounding effects on the observed patterns in coral recovery rate

To ensure that the observed reduction in recovery rate is not an artefact driven by potential confounding effects, different exploratory analyses were performed. Below is a summary of the results of these analyses.1.

1.1 Potential effect of different sites at different times (between sites versus within sites variation)

Due to the exhaustive approach taken for the exploration of all possible combinations of variables to identify the most parsimonious model, we decided not to include random effects in the statistical models presented in the main text. Instead, we included latitude and longitude as continuous predictors and forced them in all models to make sure that potential spatial autocorrelation was at least partially accounted for in the results. This approach also allowed us to explore potential spatial patterns in recovery rate over time. The assumption of this approach is that it is reasonable to expect a linear relationship between recovery rate and latitude/longitude. As recovery rate is highly dependent on coral somatic growth (among other vital rates), and there are known latitudinal and longitudinal (distance from shore) gradients of coral growth in the GBR[33], the assumption of linearity is expected. However, we acknowledge that as we are not explicitly incorporating the within vs between sites variability in the statistical models, it is possible that our results could be misleading. To confirm that between sites variability is not responsible for the apparent reduction in recovery rate over time, we conducted additional analyses for each coral type with site as a random factor and time as a fixed factor. The results are summarized in Table 1 showing that for all coral types the effect of time remains significant even when the effect of site is accounted for.

Table S1. Summary of the six permutation-based linear mixed models performed to check the effect of within-site versus between-site variability on the observed reduction in IGR.

Coral type	Factor	DF	SS	MS	Pseudo F	*p*	Unique permutations
Branching	Time (fixed)	1	0.10477	0.10477	6.5397	0.007	998
	Site (random)	205	3.4009	1.659E-2	1.437	0.308	999
	Residual	16	0.18472	1.1545E-2			
Digitate	Time (fixed)	1	2.3029E-2	2.3029E-2	5.5201	0.017	996
	Site (random)	183	0.75241	4.1115E-3	0.9008	0.626	998
	Residual	15	6.8464E-2	4.5643E-3			
Tabular	Time (fixed)	1	0.29909	0.29909	15.166	0.001	996
	Site (random)	220	4.1797	1.8999E-2	0.85556	0.726	998
	Residual	41	0.91044	2.2206E-2			
Montipora	Time (fixed)	1	7.6466E-2	7.6466E-2	7.9357	0.006	997
	Site (random)	201	1.7211	8.5626E-3	0.39858	0.976	997
	Residual	11	0.23631	2.1483E-2			
Pocillopora	Time (fixed)	1	3.6673E-2	3.6673E-2	4.9069	0.026	994
	Site (random)	218	1.4295	6.5572E-3	0.48147	0.982	998
	Residual	23	0.31324	1.3619E-2			
Massives	Time (fixed)	1	0.25128	0.25128	12.086	0.001	997
	Site (random)	221	3.3657	1.523E-2	0.28947	0.991	999
	Residual	26	1.3679	5.2611E-2			

1.2 Potential decreased ability to detect statistical breaks as coral cover declined over time.

Given that coral cover declined during the study period it is possible that our ability to detect a statistically significant reduction in coral cover also declined over time. If this is the case, the reduced recovery rate observed towards the end of the time period could have been influenced by the inclusion of only recovery periods following large perturbations. To explore this potential confounding effect, we characterized the size of identified statistical reductions in cover as well as the distribution of small identified reductions over time. The average reduction in cover was 5.1%, while the lowest reduction detected was 0.5%. 30% of the identified reductions in cover were smaller than 2%. More importantly, the number of small reductions in cover (smaller than 3%) did not change over time (Fig. 1).

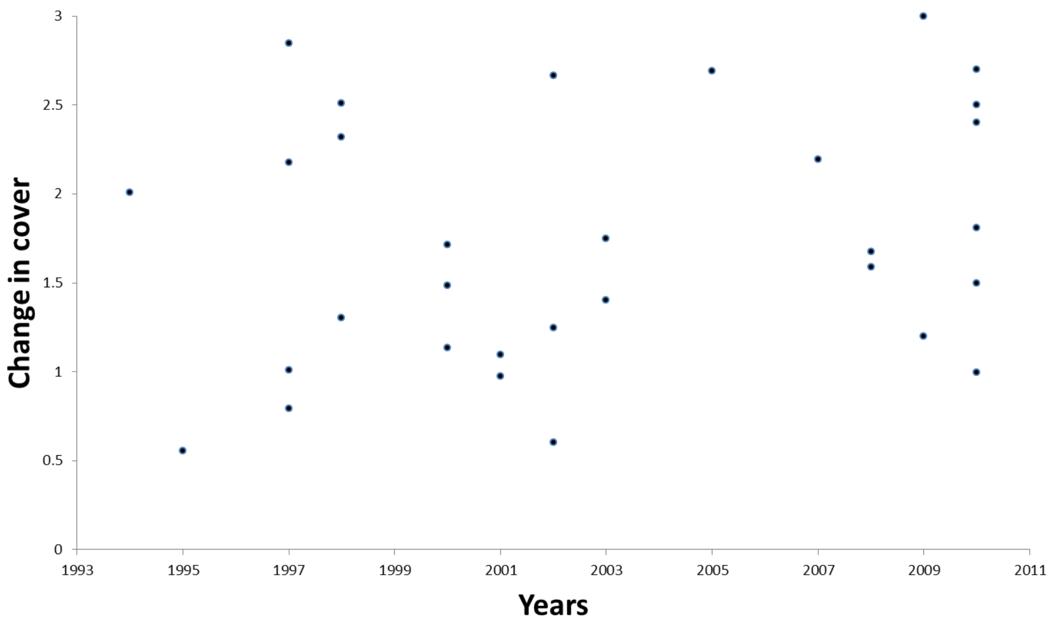

Fig. S1. Small but significant differences in coral cover (less than 3%) plotted against time. A negative trend would suggest our ability to detect significant changes decreased.

1.3 Potential effect of adding reefs (new reefs) on IGR/time relationships

Although the inclusion of sites as a random factor in the previous test accounts to a certain degree for the potential confounding effect of the additional reefs that were surveyed after 2006 (new to LTMP), we ran a new analysis where we had reef type with two levels (original and new) as a a fixed factor and time as a continuous predictor. The results shown in Table 2 suggest that the effect of time was still significant even when the effect of the new reefs is acounted for. Moreover, only for one of the six coral types (Digitate), was there a diference in the recovery rate between original and new reefs.

Table S2. Summary of the six permutation-based linear mixed models performed to check the effect of the inclusion of the new reefs [reef types with two levels (original and new)] on the observed reduction in IGR.

Coral type	Factor	DF	SS	MS	Pseudo F	*p*	Unique permutations
Branching	Time (fixed)	1	0.41457	0.41457	6.94	0.009	997
	Reef type (fixed)	1	2.4969E-2	2.4969E-2	0.41799	0.536	996
	Residual	220	13.142	5.9736E-2			
Digitate	Time (fixed)	1	2.3028E-2	2.3028E-2	5.6619	0.019	997
	Reef type (fixed)	1	1.9635E-2	1.9635E-2	4.8277	0.02	997
	Residual	197	0.80124	4.0672E-3			
Tabular	Time (fixed)	1	0.2991	0.2991	15.279	0.001	995
	Reef type (fixed)	1	2.3528E-4	2.3528E-4	1.2018E-2	0.916	997
	Residual	260	5.0899	1.9576E-2			
Montipora	Time (fixed)	1	7.6466E-2	7.6466E-2	8.3827	0.006	997
	Reef type (fixed)	1	3.2678E-2	3.2678E-2	3.5823	0.06	996
	Residual	211	1.9247	9.1219E-3			
Pocillopora	Time (fixed)	1	3.6675E-2	3.6675E-2	5.0583	0.028	997
	Reef type (fixed)	1	2.6228E-3	2.6228E-3	0.36175	0.537	998
	Residual	240	1.7401	7.2503E-3			
Massives	Time (fixed)	1	0.25128	0.25128	13.125	0.001	994
	Reef type (fixed)	1	2.3949E-2	2.3949E-2	1.2509	0.228	996
	Residual	246	4.7097	1.9145E-2			

1.4 Potential effect of the fact that some recovery periods start with the first visit to a site while others start with an observed statistically significant reduction in coral cover.

Some recovery trajectories begin with the first visit to a site while others start after a significant reduction (pertubation) in coral cover (see methods sections on min text for details). Therefore, we ran a new analysis to test whether trajectory type influenced relationships between recovery rate and time. This new analysis included trajectory type (time series type) with two levels (starting with first visit to site or starting after a significant reduction in cover) as a fixed factor, and time as a continuous predictor. Table 3 shows how time remains significant for all taxa even when the effect of the trajectory type is accounted for. Moreover, the type of recovery period only had a significant effect in 3 of the six coral types (Digitate 0.022, 0.056, Montipora 0.011, 0.077 and Massives 0.044, 0.1).

Table S3. Summary of the six permutation based linear models performed to check for the effect of the different starting points for each recovery trajectory [trajectory type with two levels (starting with first visit or starting after reduction in coral cover)] on the observed reduction in IGR.

Coral type	Factor	DF	SS	MS	Pseudo F	*p*	Unique permutations
Branching	Time (fixed)	1	0.41457	0.41457	6.9859	0.011	997
	Trajectory type (fixed)	1	0.11132	0.11132	1.8759	0.161	999
	Residual	220	13.056	5.9344E-2			
Digitate	Time (fixed)	1	2.3028E-2	2.3028E-2	5.7382	0.018	998
	Trajectory type (fixed)	1	3.0281E-2	3.0281E-2	7.5455	0.007	997
	Residual	197	0.79059	4.0131E-3			
Tabular	Time (fixed)	1	0.2991	0.2991	15.281	0.001	995
	Trajectory type (fixed)	1	1.1189E-3	1.1189E-3	5.7163E-2	0.809	996
	Residual	260	5.089	1.9573E-2			
Montipora	Time (fixed)	1	7.6466E-2	7.6466E-2	8.5523	0.003	995
	Trajectory type (fixed)	1	7.0851E-2	7.0851E-2	7.9243	0.007	998
	Residual	211	1.8865	8.941E-3			
Pocillopora	Time (fixed)	1	3.6675E-2	3.6675E-2	5.0528	0.032	997
	Trajectory type (fixed)	1	7.1214E-4	7.1214E-4	9.8114E-2	0.75	996
	Residual	240	1.742	7.2583E-3			
Massives	Time (fixed)	1	0.25128	0.25128	13.491	0.001	996
	Trajectory type (fixed)	1	0.1515	0.1515	8.1335	0.007	997
	Residual	246	4.5821	1.8627E-2			

Section S2. Projected recovery of reefs in different regions of the GBR as a function of different disturbance regimes

In the main text of the paper we presented the projected recovery of a particular reef (Reef 19138 as an example). Here, we extend that approach to include three additional examples one each from the northern, central and southern part of the GBR. We used the Great Barrier Reef Marine Park Authority's delimitation of GBR regions. We use our statistical model to predict IGR and calculate coral recovery under possible future disturbance scenarios. The variables used for model predictions included geographic location of each specific reef, an initial coral cover of 5% in year 2010, and different levels of chronic and acute disturbances. As shown in Fig. 1, reefs in all three region show fast recovery when there has been no recent acute disturbances and chronic disturbances are removed. Both the legacy effects of acute disturbances, and chronic disturbances (in this case water quality) significantly reduce the ability of reefs to recover. When both types of disturbances are combined, reef recovery is greatly reduced.

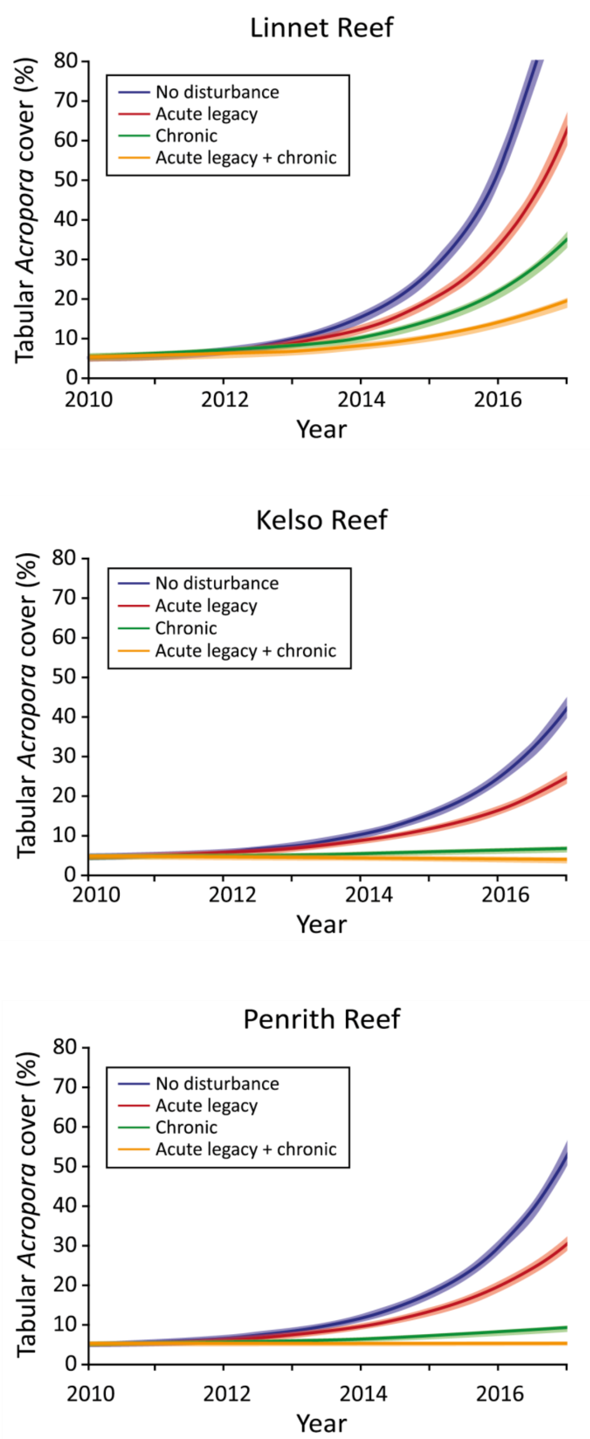

Fig. S2. Projected recovery after the studied period under different disturbance scenarios for three GBR reefs (Linnet Reef in the northern, Kelso Reef in the central, and Penrith Reef in the southern part of the GBR). Lines show the projected coral cover the reef would follow based on the IGR predicted from the statistical model. Shade shows variability when the parameters are varied by 5%.

Section S3. Comparing IGR estimates

We opted to use endpoints to calculate IGR (our dependent variable) because we considered the outcome of the recovery period (the final measurement) to be a more important indicator of reef performance than mean performance over the entire period. However, IGR estimates were very similar (Pearson's correlation coefficient: 0.975) whether calculated using endpoints or exponential fits of all sample points within a recovery trajectory (fig. S3).

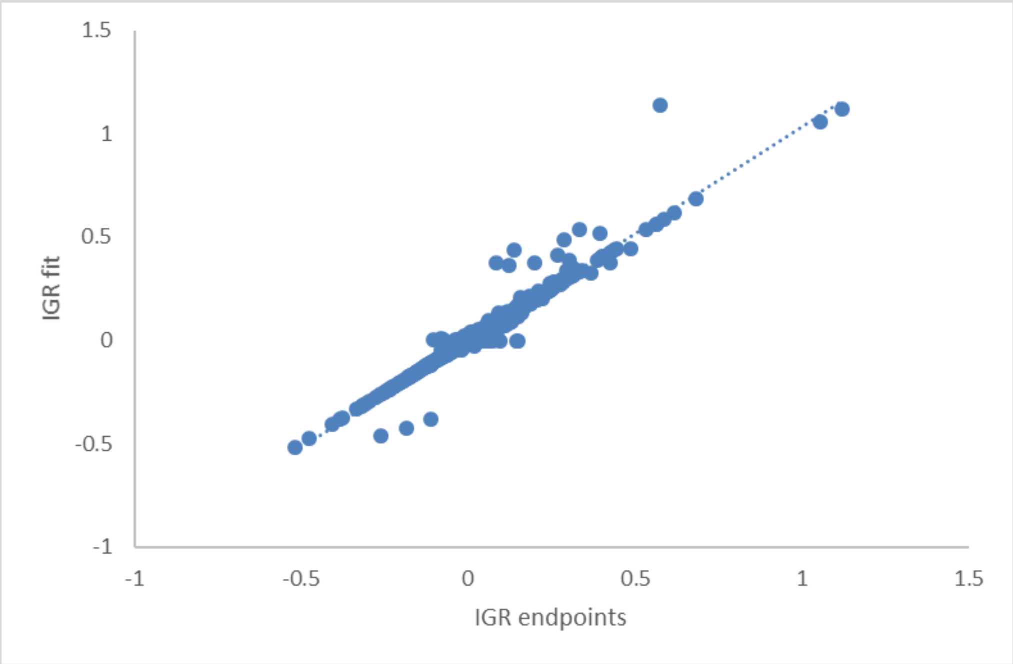

Fig. S3. For this study, we calculated the IGR of recovery periods (*n* = 1392) using recovery trajectory end points (first and last). Here we compare IGR values calculated using the endpoint approach versus IGR values estimated using an exponential fit of the entire recovery trajectory (all samples).

Section S4. Identification of recovery periods

Here we include example time series analyses for each of the six taxa explored in this paper.

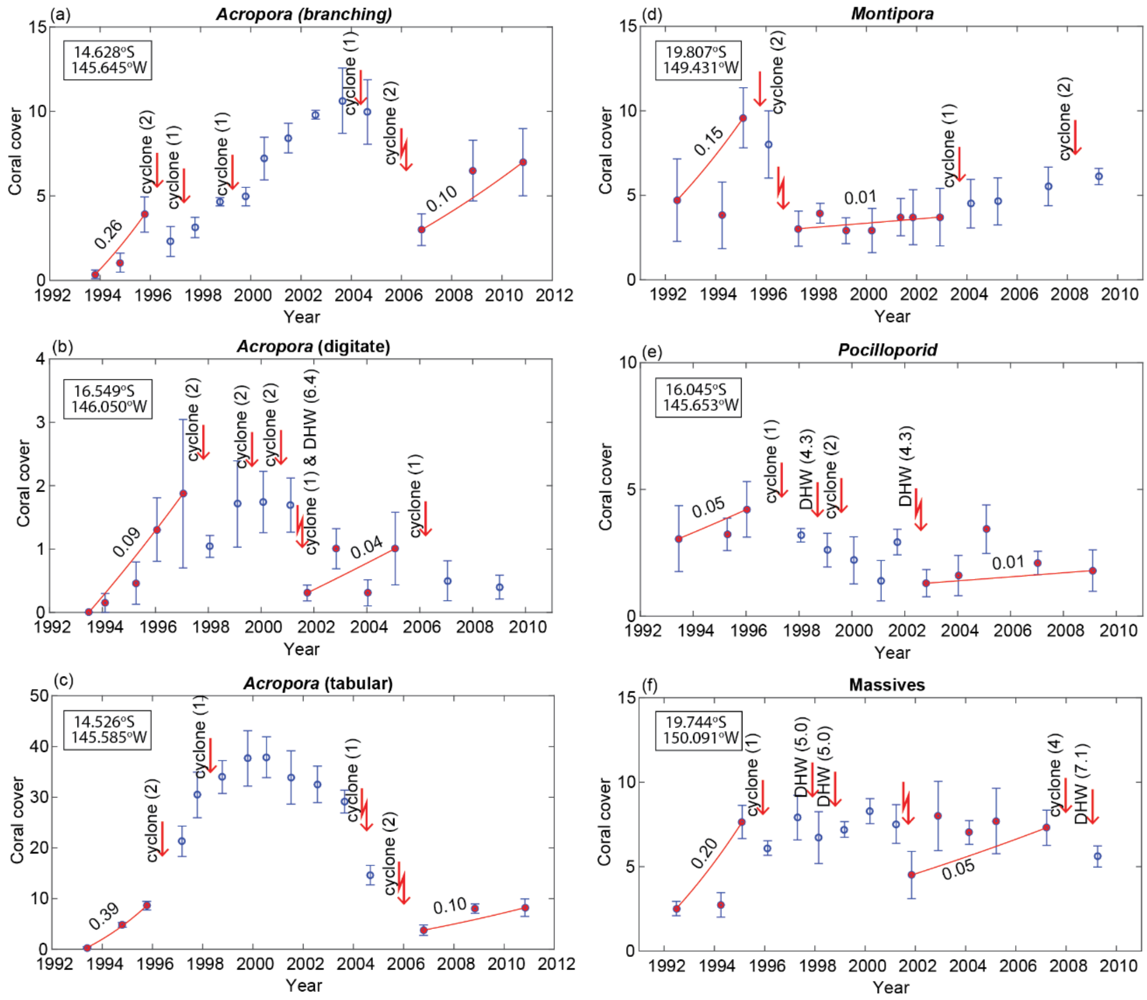

Fig. S4. Example time-series for each of the six taxa groups explored here. *Acropora* branching (**a**), *Acropora* digitate (**b**), *Acropora* tabular (**c**), *Montipora* (**d**), Pocilloporid (**e**) and massives (**f**). Location of each site is shown in box in upper left of each panel. Sample points (circles) represent mean coral cover (%) during each visit estimated from five permanent transects located at sites. Error bars represent standard error of the mean. Recovery trajectories (filled circles) were identified using the criteria explained in Methods and in fig. S3 caption. End points of recovery trajectories were used to estimate IGR (shown in text above fitted line), the response variable used in this study. Also shown are approximate timing of all observed acute disturbances (red arrow) that occurred between sample visits. The numbers after disturbance type indicate magnitude of disturbance. The values in parenthesis represent either the category of cyclones (1 – 5), the COTS outbreak density (>1) estimated from manta tow or the degree heating weeks (DHW>4) estimated from NOAA's Coral Reef Temperature Anomaly Database (CoRTAD). Significant breaks are illustrated with jagged red arrows. Note that not all significant breaks were explained by acute disturbances explored in this study.

Section S5. Spatial autocorrelation of reef IGR

In Fig. 2 we use a map to display the spatial distribution of change in reef recovery rates (IGR) for tabular corals of the genus *Acropora*. Temporal change in IGR was calculated per reef [(later – earlier)/earlier] using mean IGR for cases where a reef had multiple trajectories per time period. In the cases where a reef did not have a value for the before or after period, inverse distance weighted interpolation was used to obtain the corresponding value. This interpolation approach was justified because Moran's *I* test revealed that both the before (I=0.247) and after (I=0.507) reef IGR values were significantly ($p<0.05$) spatially autocorrelated (clustered). Further, a semivariogram of reef IGR (fig. S5) revealed a spatially autocorrelated range of 35.3 km, over three times greater than the mean nearest neighbour distance of 11 km among reef locations. This results suggest that the interpolation we did is likely to be appropriate, as the reefs we interppoleated form are likely to be highly correlated as the distance between them is much smaller that the range of the semivariogram Semivariogram was calculated using the variogram and variogramfit functions within Matlab (vers 8.6).

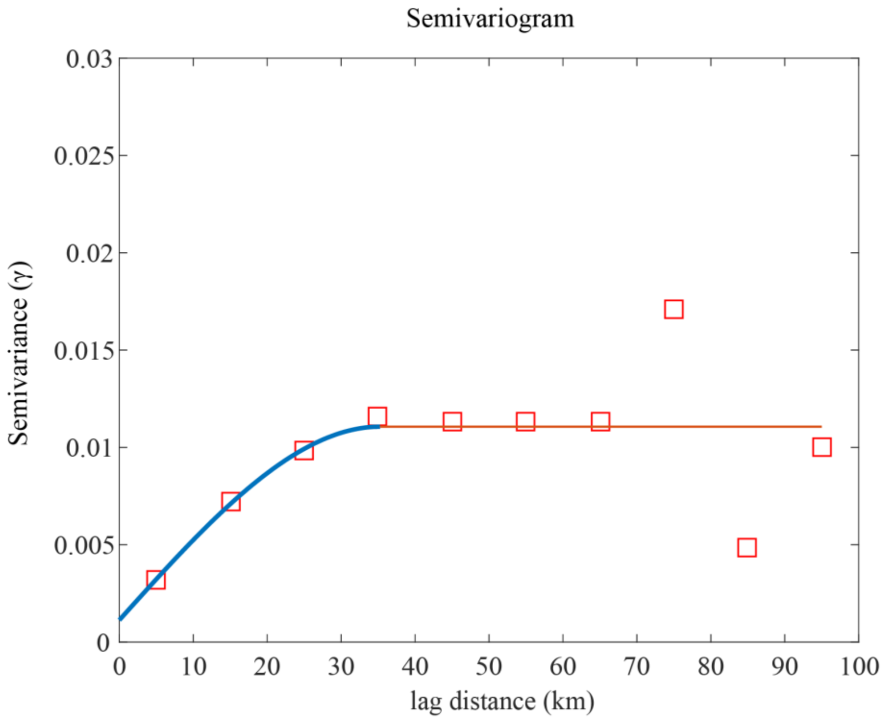

Fig. S5. Semivariogram of reef tabular *Acropora* IGR. The mean semivariance is shown for reefs binned according to distance from pairwise comparisons (red box). Variogram fit is shown as line, with the blue portion showing the range (<= 35.3 km).