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Supplementary Materials for

Transformation of coral communities subjected to an unprecedented heatwave is modulated by local disturbance

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The PDF file includes:

Supplementary Methods
Figs. S1 to S13
Tables S1 to S9
Legend for data S1
References

Other Supplementary Material for this manuscript includes the following:

Data S1

Supplementary Methods

Study Site

Kiritimati, an atoll within the Republic of Kiribati, supports approximately 6,500 people (*81*), the vast majority of whom are highly dependent on reef resources for subsistence and income due to the atoll's geographic isolation and limited alternate livelihoods (*13, 82*). Reef fish in particular are a vital resource, with over 95% of households on Kiritimati actively engaged in fishing activities (*82*). Since 2009, we have monitored forty coral reef sites around the atoll: thirty-seven of the sites were initially established in 2007 by Walsh (*85*) and three additional sites were added in 2009. Included herein are the nineteen sites at which we surveyed benthic community composition at least once in the two years before the 2015–2016 El Niño (July 2013–May 2015) and at least once in the year after the event.

Chronic Local Human Disturbance

Kiritimati's spatial gradient of chronic local human disturbance arose because of the concentration of villages and infrastructure on the northwest coast (Fig. S2, table S1). In addition to the villages, there has been extensive dredging for a port near one of the sites on this coast (VH1). Kiritimati also does not have a sewage treatment plant (*45*), and run-off is known to lower water quality on coral reefs (*78*, *79*). Reefs elsewhere on the atoll are subject to minimal local human disturbance. In particular, coral reefs in the Bay of Wrecks and on the eastern side of Vaskess Bay (Fig. S2) experience virtually no direct local human impacts, as there are no villages or infrastructure whatsoever in these areas.

Previous studies have noted Kiritimati's gradient in local human disturbance and the degraded state of Kiritimati's reefs near the atoll's villages. When surveyed in 2007, Walsh (*85*) found that both top predator and carnivorous fish biomass were significantly lower at sites with elevated fish catches (i.e., primarily those categorized herein as 'very high' or 'high' disturbance) compared to those at sites with lower catches (i.e., 'medium', 'low', and 'very low' disturbance sites). Focusing on the microbial and benthic component of the reef ecosystem, Dinsdale et al.'s (*45*) study from across the northern Line Islands, which sampled only reefs across Kiritimati's lagoon face, reported that Kiritimati's reefs had ten times as many microbial cells and virus-like particles in the water column as on uninhabited Kingman Reef. Kiritimati's microbes were reportedly dominated by heterotrophs, including a high proportion of potential pathogens, and the benthic community was said to have the highest prevalence of coral disease of the four surveyed northern Line Islands (*45*). Of the sites sampled on Kiritimati, those in the very high disturbance region (i.e., north of the lagoon) had higher microbial counts and higher counts of culturable *Vibrio* spp. than the site sampled on the south lagoon face (close to our sites that are categorized as medium disturbance) farther from the villages (*45*). More recently, McDevitt-Irwin et al. (*46*) showed that sites on Kiritimati exposed to very high disturbance (VH1, VH2) had significantly higher bacterial counts in the water column (near the coral substrate) compared to sites exposed to very low disturbance (VL1, VL2).

We tested whether our quantitative metric of local human disturbance was correlated with three other indicators of disturbance (sedimentation, turbidity, and microbial load) for our nineteen surveyed sites (Fig. S3). As a proxy for sedimentation, we used our benthic photoquadrat data to calculate an estimate of the percent of the substratum covered by sediment. We calculated this ‘percent sediment’ metric both including and excluding sand. As a proxy for turbidity, a single experienced scientific diver (K. Tietjen) estimated visibility at each dive site. On expeditions where a site was sampled on more than one day (up to n = 3), these estimates were averaged. We then averaged this visibility across all expeditions for which we had data for a given site. As expected, sites nearest to villages had lower visibility (mean = 14.5 m) than those with the lowest disturbance (mean = 32.3 m; Fig. S3). We tested for relationships between human disturbance and a) percent sediment cover (without sand), b) percent sediment cover (with sand), and c) visibility using linear models. Finally, we re-evaluated the data from McDevitt-Irwin et al. (*46*) on the concentration of bacteria in the water column at four sites on Kiritimati (two very high and two very low human disturbance). These data were collected by taking water samples (1–2 mL), preserving them in formaldehyde, then filtering the samples and counting DAPI-stained bacteria under high magnification. The mean concentrations of microbes at each site (n = 4 samples each) were then compared using a one-way ANOVA and a Tukey post-hoc test (Fig. S3d).

Oceanographic Factors

Beyond anthropogenic impacts, natural oceanographic factors including sea surface temperature, oceanographic productivity, and wave energy can influence coral reef ecosystem structure and diversity (*99-102*). To assess the extent to which such features might explain differences in benthic community composition around Kiritimati atoll, we quantified multiple oceanographic and abiotic variables at our nineteen sites (table S2; water temperature is described in the section below in the context of heat stress). At each site, we quantified *in situ* salinity, dissolved oxygen (DO) saturation, and pH using a YSI Pro Plus handheld multiparameter meter that was calibrated daily and collected water samples to quantify nutrients (i.e., phosphate, silicate, nitrate, nitrite) (table S2). We supplemented these *in situ* measurements with remotely sensed data, using the Marine Socio-Environmental Covariates (MSEC) open source data product (*83*) to obtain estimates of oceanographic productivity and wave energy (table S2), as follows: *1)* maximum net primary productivity (NPP; mg C m^{-2} day^{-1}) values in MSEC were calculated over a 2.5 arcmin grid based on data from NOAA CoastWatch, which models NPP using satellite-derived measures of photosynthetically available radiation (PAR), sea surface temperature (SST), and chlorophyll-*a* concentrations; *2)* mean wave energy (kW m^{-1}) in MSEC is computed from the WAVEWATCH III hindcast dataset. We excluded the data for sites in which an estimate was made from wind and fetch values rather than the WAVEWATCH III data, detailed in (*83*).

With the exception of primary productivity, which is known to vary across Kiritimati’s reefs due to island-wake upwelling that occurs along the atoll’s western side (*85*), there was little variation in these oceanographic and water chemistry characteristics amongst sites around the atoll (table S2). We note, however, that although long-term mean wave energy values at our sites were quite similar, ranging only from ~25 to 27 kW m^{-1}, reliable WAVEWATCH III data were not available for several sheltered sites along the lagoon face; thus, these data may not capture the true variability in wave energy across the atoll. We therefore also defined a site exposure variable based upon the predominant wind direction that included all sites (*84*) and employed this variable in our statistical models.

Data Processing

Benthic Community Data

For each photo of the benthic community (n = 2,649; table S7, S8), we first cropped the image around the quadrat and checked the white balance, adjusting those photos that still had color casts due to technical issues underwater. In CoralNet (*86*), we then manually annotated the substrate beneath each of the 100 random points and identified corals to either genus or species, based on the functional relevance of each coral to the project and our ability to distinguish species from photographs. 'Sediment' was defined as sand covering another substrate such as a dead coral, whereas 'sand' was used when there was no visible substrate underneath. Points that could not be annotated (e.g., the taxonomic identity could not be resolved because the point fell on a dark shadowed area) were excluded from the dataset for downstream analysis. If a photo had more than 10 points that could not be annotated, it was excluded from the dataset entirely; this resulted in 12 photos (0.42% of photos) being removed from the data set, for a final total sample size of 2,637 (table S7, S8).

Statistical Analyses

Coral Cover Models

The coral cover models presented in the main text were fit using a dataset in which values for each site were averaged across expeditions conducted in the same heatwave period (i.e., 'before' or 'after') (table S8). This dataset had the advantages of having data for all nineteen sites in both heatwave periods; an even representation of sites, with one data point per site per heatwave period; and the most comprehensive coral cover estimates (due to the greater number of quadrat photos used to produce the estimate). To assess the robustness of our results, we also ran the models using two different forms of the data: (a) using all available data points, such that some sites had more than one data point per heatwave period because they were sampled in multiple expeditions, and (b) using only the data from the largest expedition in each heatwave period (July 2013 for the 'before' period and July 2017 for the 'after' period) (table S8). Models were fit using the same parameters as the main models, with the addition of expedition as a random effect where required. Both of these alternate datasets had minimal effect on the model results for all of the models presented, with all conclusions of the paper regarding heat stress and local human disturbance effects holding regardless of the dataset used (see table S4).

Model performance for all GLMs and GLMMs was assessed using the *performance* package (*103*). Conditional (where applicable) and marginal R^2 values were calculated for each model using the 'model_performance' function, and model fit was further examined visually using the posterior predictive check plot output by the 'check_model' function. Further model diagnostics were performed using the *DHARMa* package (*98*) which was used to calculate scaled residuals for each model and output residual plots that are specially formulated for assessing GLMMs (but can also be used for GLMs). For the models presented in the main text, we found that initial problems with residuals could be alleviated, or at least minimized, by including additional environmental covariates in the model (i.e., NPP) and/or modelling them with a quadratic relationship to account for non-linearity. For the two additional datasets described above, problems with residuals (e.g., patterns in the residual plots) sometimes could not be resolved without the use of more complex polynomial relationships; therefore, for direct comparison with the main text models, we present these additional models using the same covariates (table S4). However, open source code allows for additional testing (https://github.com/baumlab/Baum_etal_2023_ScienceAdvances).

Supplementary Figures

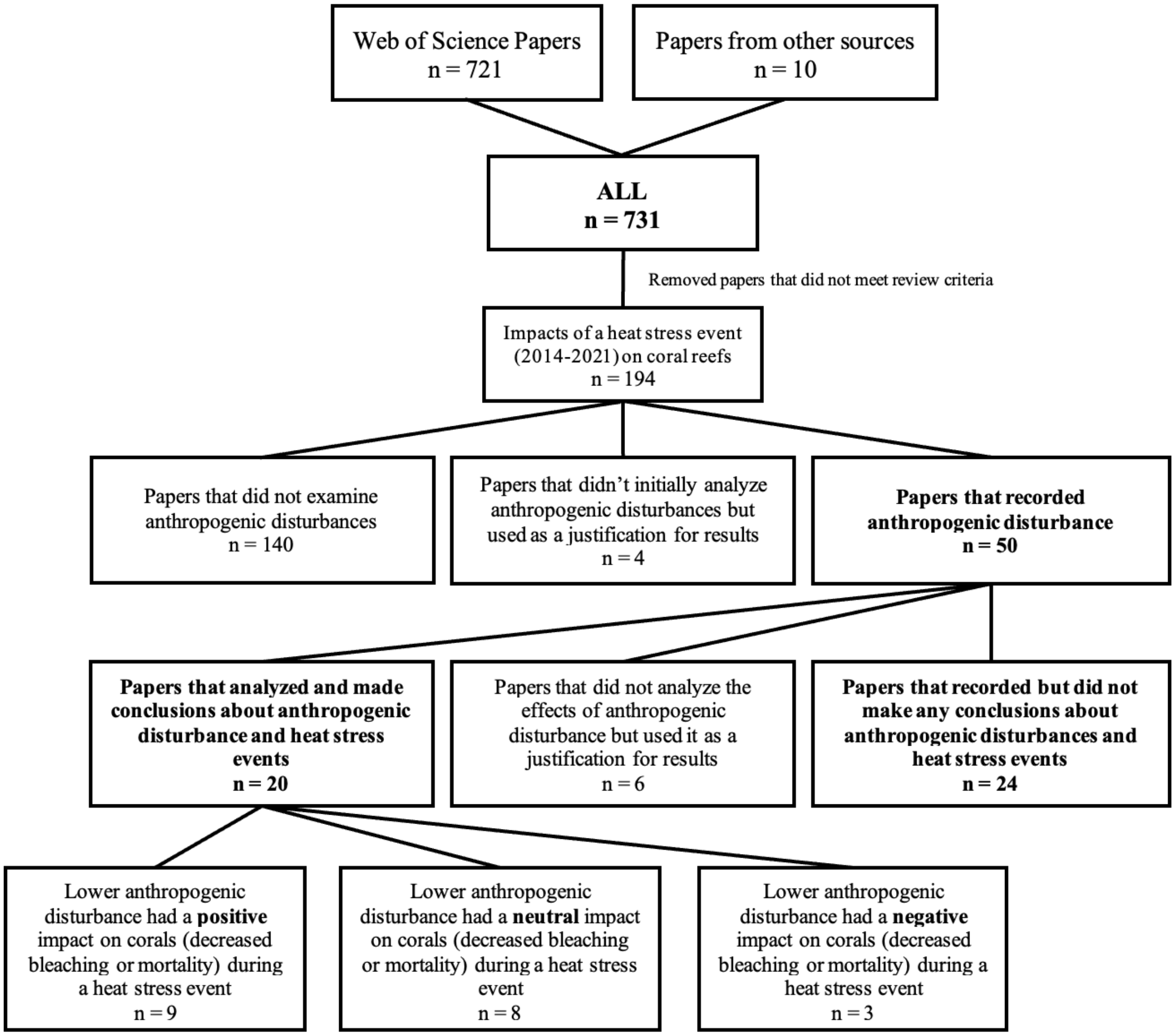

Fig. S1. PRISMA diagram showing results of the systematic review of the primary literature to quantify the extent to which field studies that had assessed the impacts of recent marine heatwaves (2014 to 2021) on corals quantified underlying anthropogenic stressors at their study site and tested for an effect of them on coral outcomes through the heat stress event.

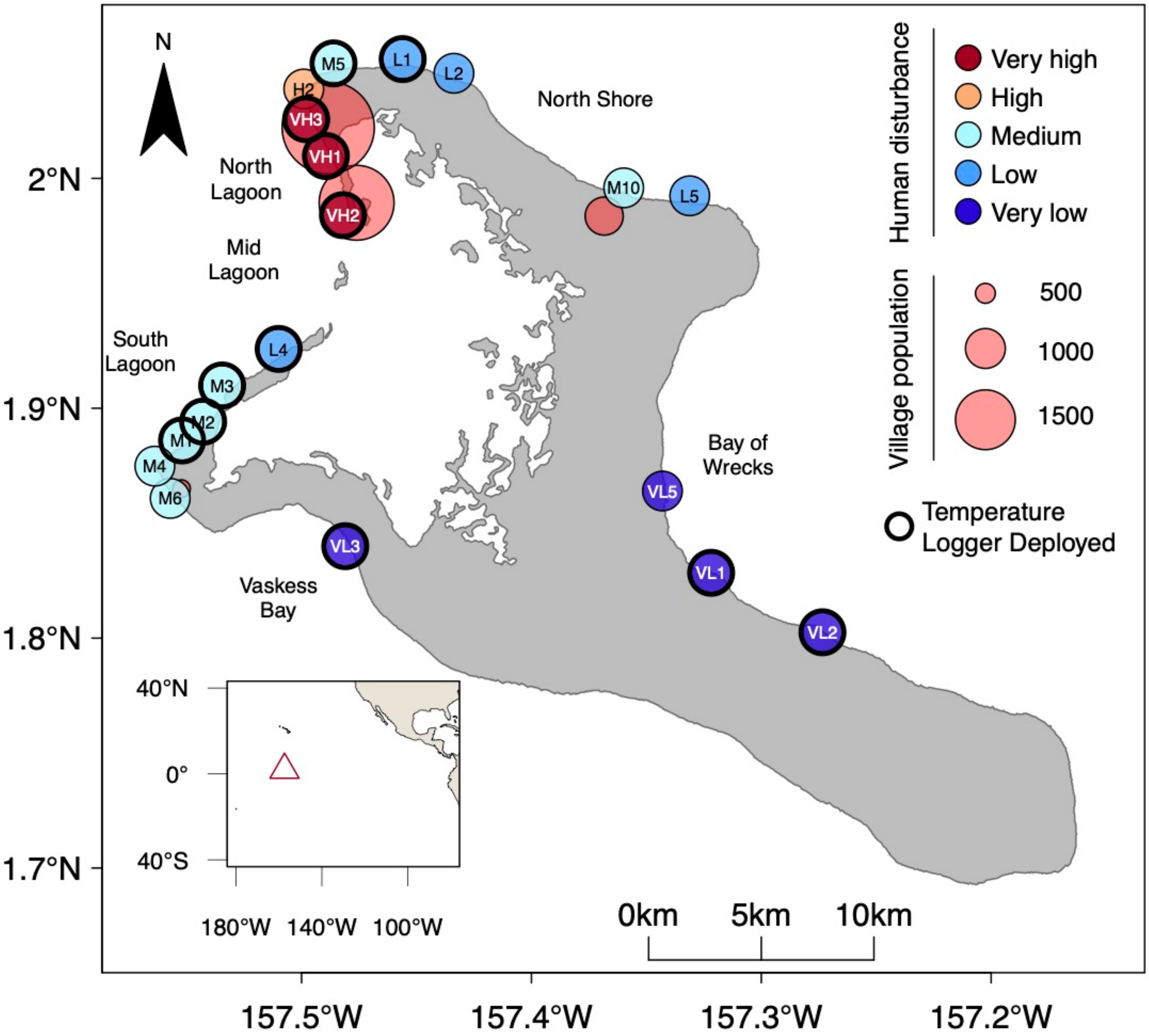

Fig. S2. Kiritimati (Christmas Island), showing nineteen forereef sites (and their site names, as in tables S1–S3) at which benthic community composition was quantified between 2013 and 2017. Sites are categorized by relative level of chronic local human disturbance (detailed in table S1), and villages (pink circles) are scaled to human population size. Sites at which high-precision *in situ* temperature loggers were deployed between 2011 and 2017 are circled in black. Inset shows Kiritimati's location in the central equatorial Pacific Ocean.

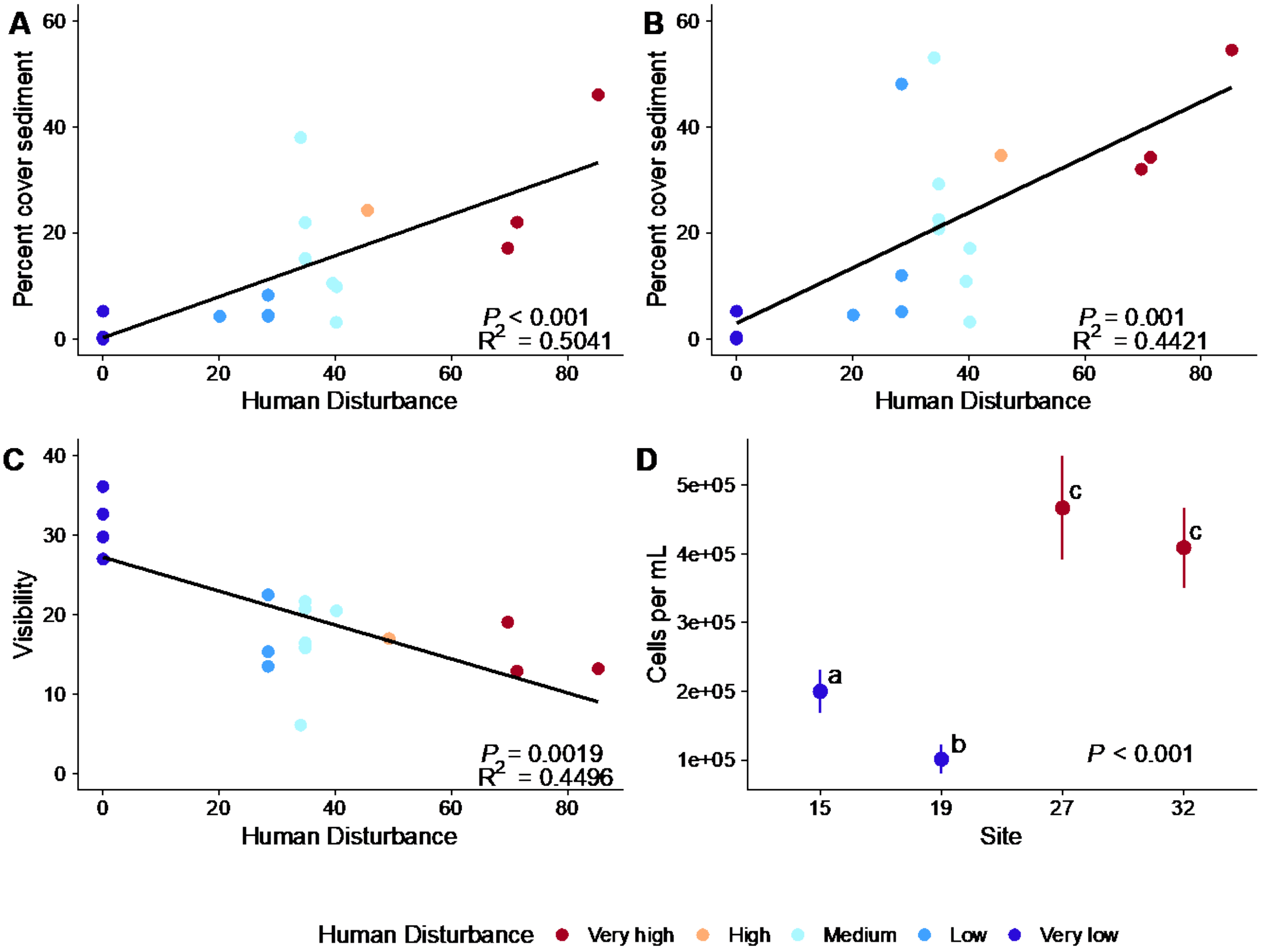

Fig. S3. Indicators of human disturbance across Kiritimati atoll. A and **B**) Relationship between benthic sediment cover, both without (**A**) and with (**B**) sand included, and chronic local human disturbance (sqrt(LocalDisturb)); (**C**) Relationship between water column visibility (a proxy for turbidity) and the human disturbance index; (**D**) Comparison of microbial counts at two very high disturbance and two very low disturbance sites; data from McDevitt-Irwin *et al.* (*46*). Letters indicate significant differences between means as determined by a Tukey post-hoc test.

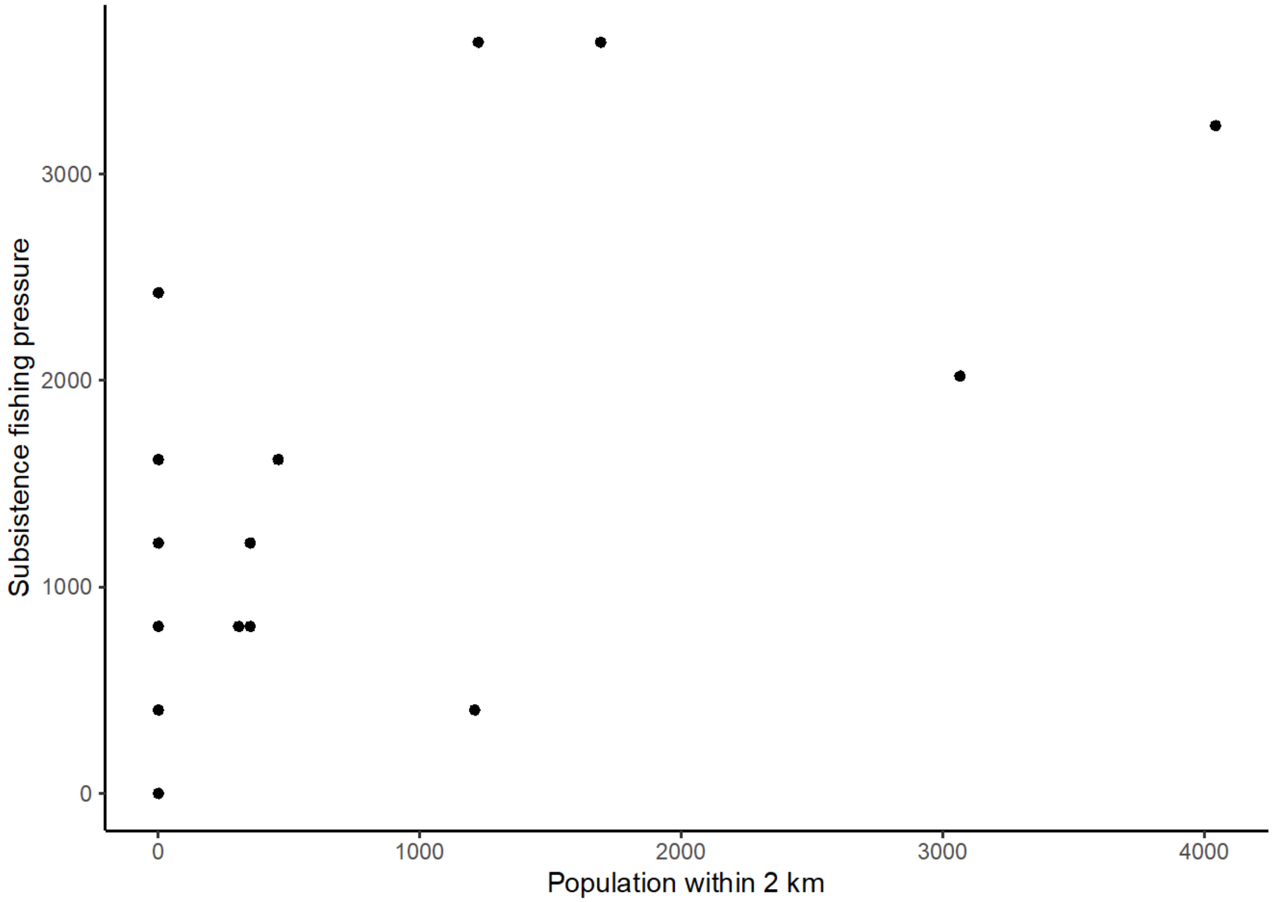

Fig. S4. Relationship of variables that make up the combined human disturbance metric. The population residing within 2 km of each site is based upon the Government of Kiribati's 2015 population census data for each village on Kiritimati (*81*) and is used as a proxy for localized impacts. Subsistence fishing pressure was quantified through detailed semi-structured interviews conducted with heads of household in each of the atoll's villages in 2013 (*82*) and is represented using a kernel density function as a measure of its intensity at each site.

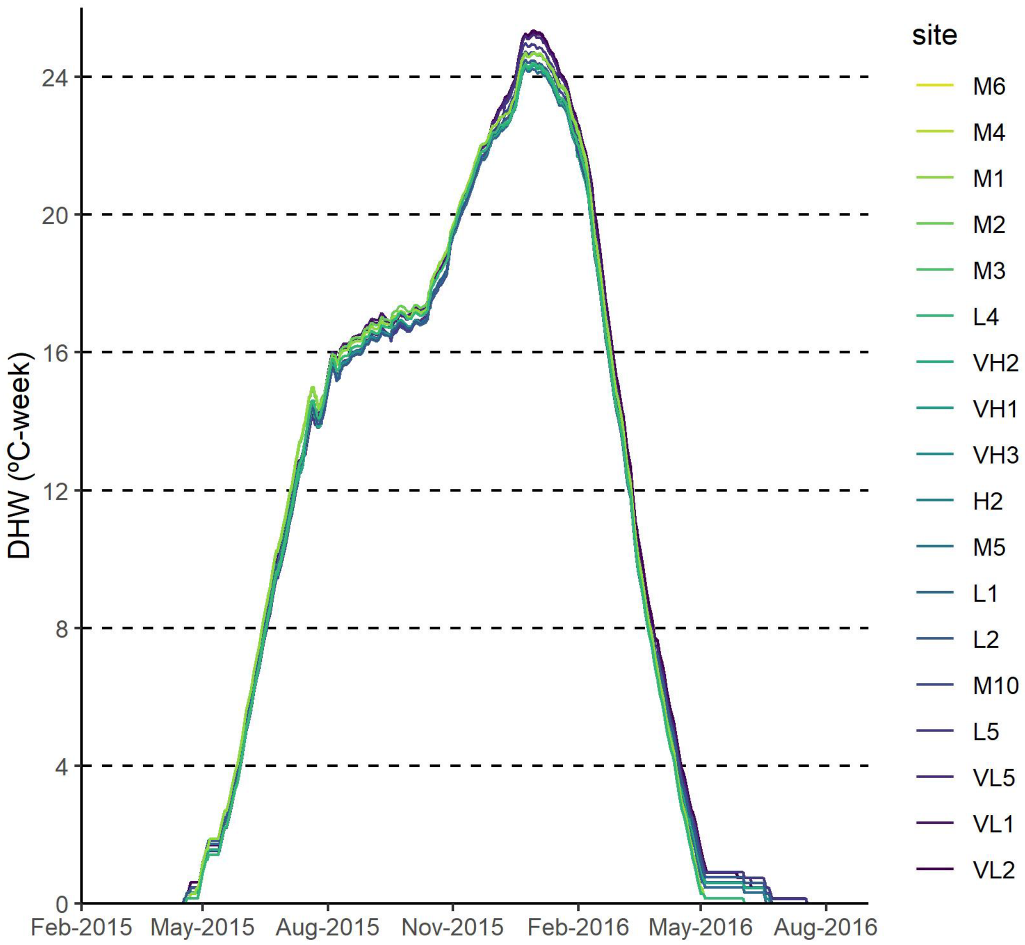

Fig. S5. Thermal stress at each site on Kiritimati atoll during the 2015–2016 El Niño event, measured in degree heating weeks (DHW, °C-weeks) from NOAA Coral Reef Watch (CRW). Site colors are ordered clockwise from the southwest side of the island.

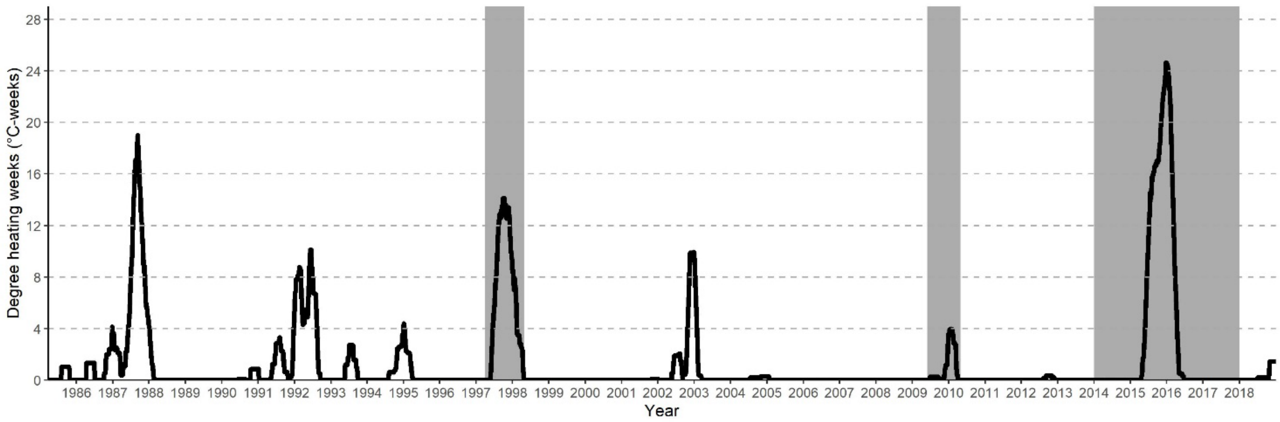

Fig. S6. Long-term thermal stress on Kiritimati, plotted as mean degree heating weeks (DHW, °C-weeks; across all nineteen study sites) experienced over the last thirty-four years (1985–2019) from NOAA Coral Reef Watch's (CRW) satellite-derived data product. Grey shaded areas denote the timing of the first global coral bleaching event (caused by the 1997–1998 El Niño), the second global coral bleaching event (caused by the 2009–2010 El Niño), and the third (2014–2017) global coral bleaching event (*11*).

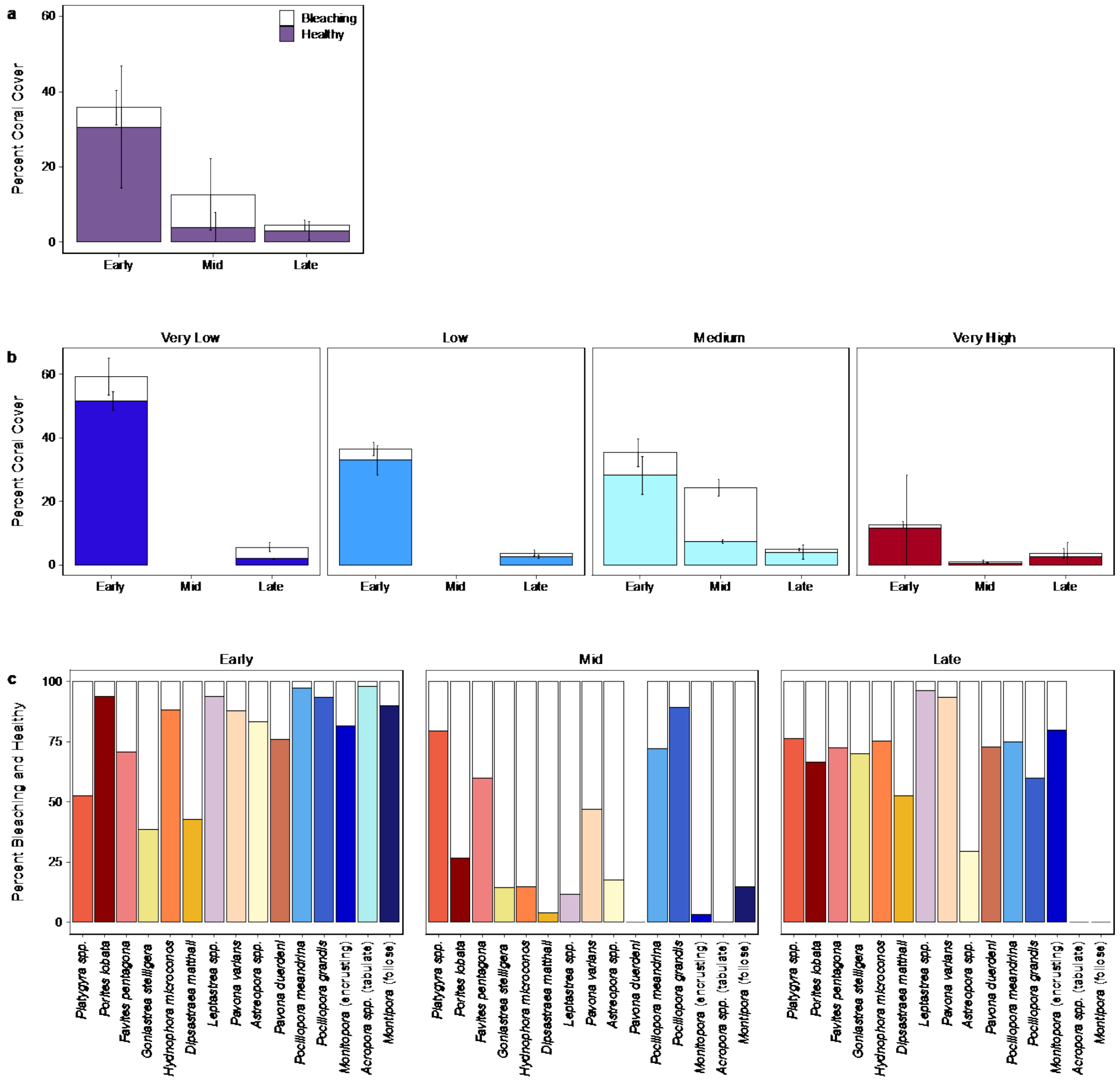

Fig. S7. Extent of bleached coral at three time points during the prolonged 2015–2016 heatwave. Early = July 2015 (two months heat stress); Mid = November 2015 (six months heat stress); Late = late March/April 2016 (ten months heat stress). Percent bleaching vs. healthy hard coral cover (out of total benthic community composition) (**A**) across all sites, (**B**) across sites within each human disturbance category, and (**C**) for the fifteen most common hard coral species on Kiritimati (prior to the El Niño), averaged across the atoll, showing the progression of bleaching across the three time points. Species are ordered left to right from highest to lowest overall survival on the atoll by end of the heatwave. Plots include the 14 sites that were sampled during the heatwave (very low (VL1–VL3), low (L1, L2, L4), medium (M1–M5), high (none), very high (VH1–VH3)); the remaining five sites were only sampled before and after the event.

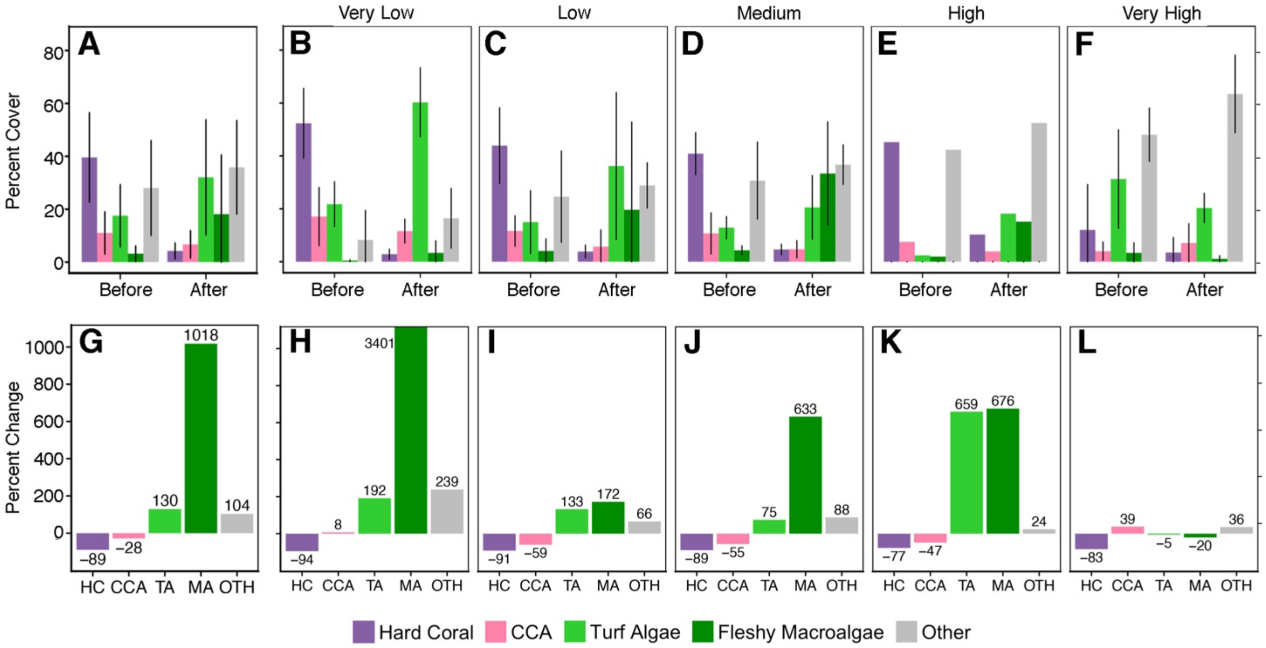

Fig. S8. Change in overall benthic community composition on Kiritimati's reefs as a result of the prolonged 2015–2016 El Niño heatwave, for means of all sites (**A, G**), and (**B**–**F**, **H**–**L**) means of the sites within each of the five human disturbance levels. (**A**–**F**) show percent cover of hard coral (HC), crustose coralline algae (CCA, also includes *Peyssonnelia* spp.), turf algae (TA), fleshy macroalgae (MA), and other substrates (OTH, sand, sediment, rubble, consolidated rock (i.e., exposed white calcium carbonate), soft coral) before (July 2013–May 2015) and after (November 2016, July 2017) the heatwave; **(G**–**L**) show the percent change for each benthic community component over this period.

Fig. S9. Estimated coral cover at sites dominated by competitive or stress-tolerant coral species (or 'mixed' sites with no dominant life history type) before (2013–2015) and after (2016–2017) the 2015–2016 El Niño. Larger points represent predicted values (mean ± 95% confidence interval) extracted from the model, while smaller points represent observed values.

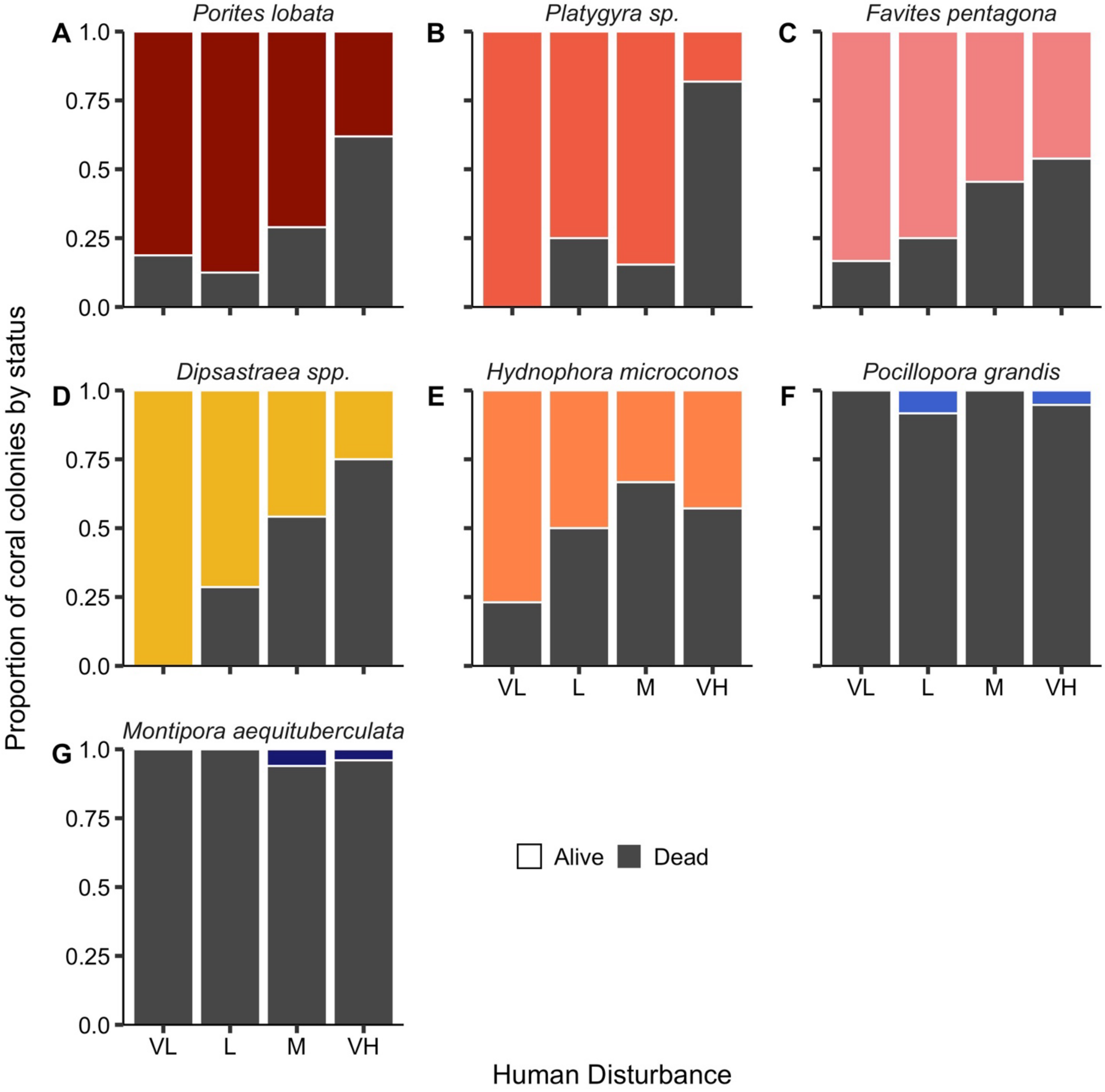

Fig. S10. Proportion of coral colonies of each species that survived (with species colour-coded as in Fig. 5f and Fig. S11-S13) or died (grey), with sites categorized by chronic local human disturbance (VL = very low; L = low; M = medium; VH = very high).

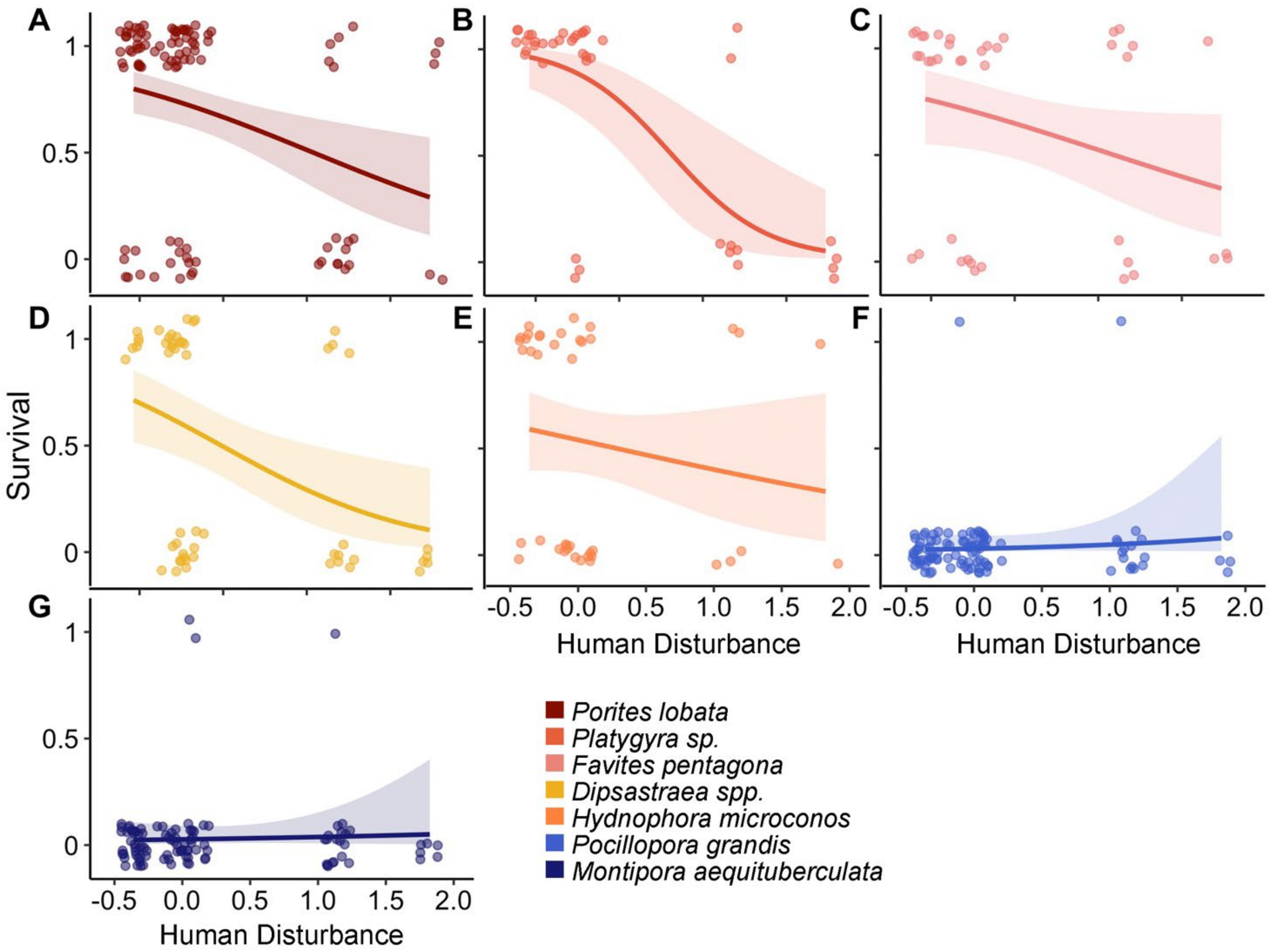

Fig. S11. Relationship between survival (= 1 vs. 0 = mortality) of individual coral colonies and chronic local human disturbance, by species (colour-coded as in Fig. 5f and Fig. S10, S12, S13). Circles are individual colonies (points were x and y jittered for visualization), solid lines are the logistic regression estimate with shading denoting the 95% confidence intervals.

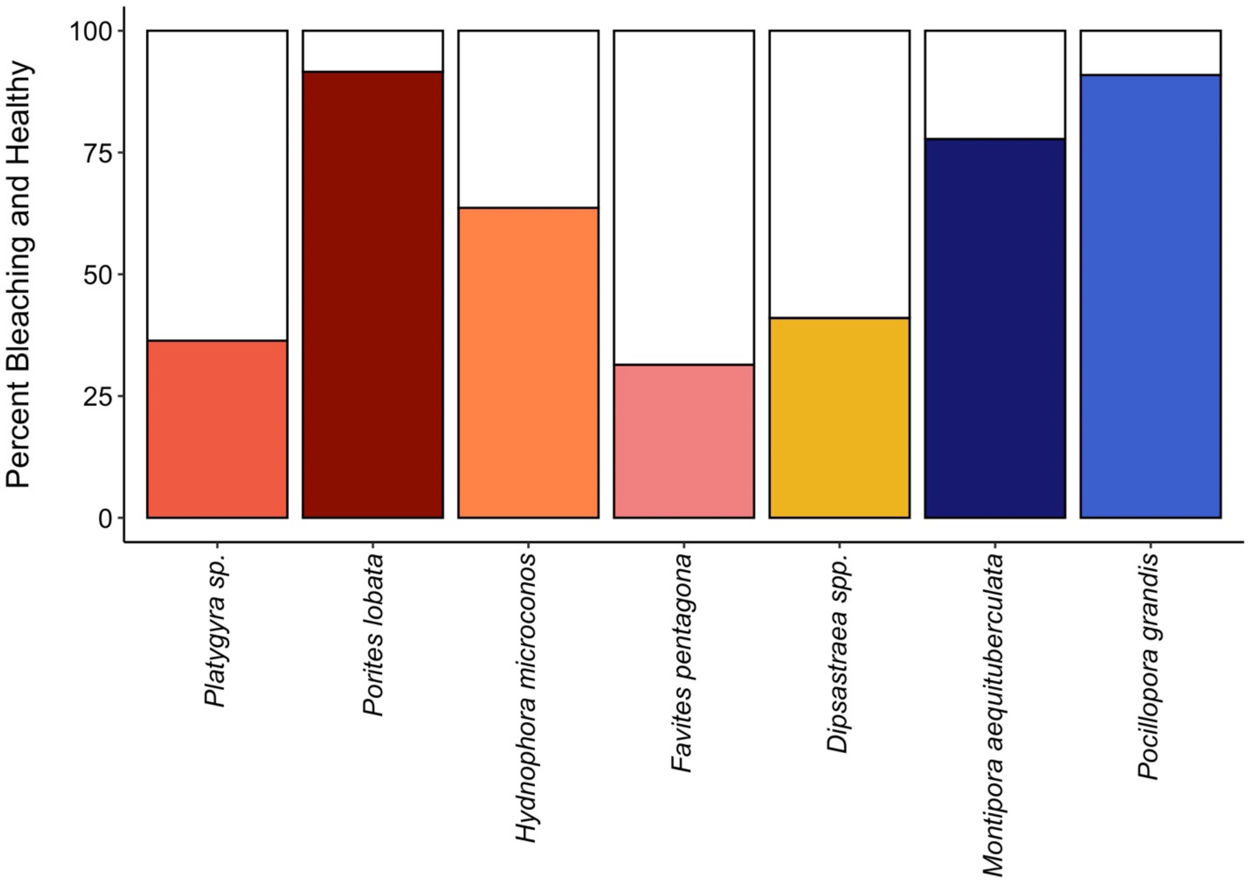

Fig. S12. Incidence of bleaching in tagged coral colonies early in the El Niño (July 2015). Percent bleaching (white portion) vs. healthy (colored portion, colour-coded as in Fig. 5f and Fig. S10, S11, S13) in tagged coral colonies across all sites on Kiritimati. Species are ordered left to right from highest to lowest overall survival (using tagged coral data) on the atoll by end of the heatwave.

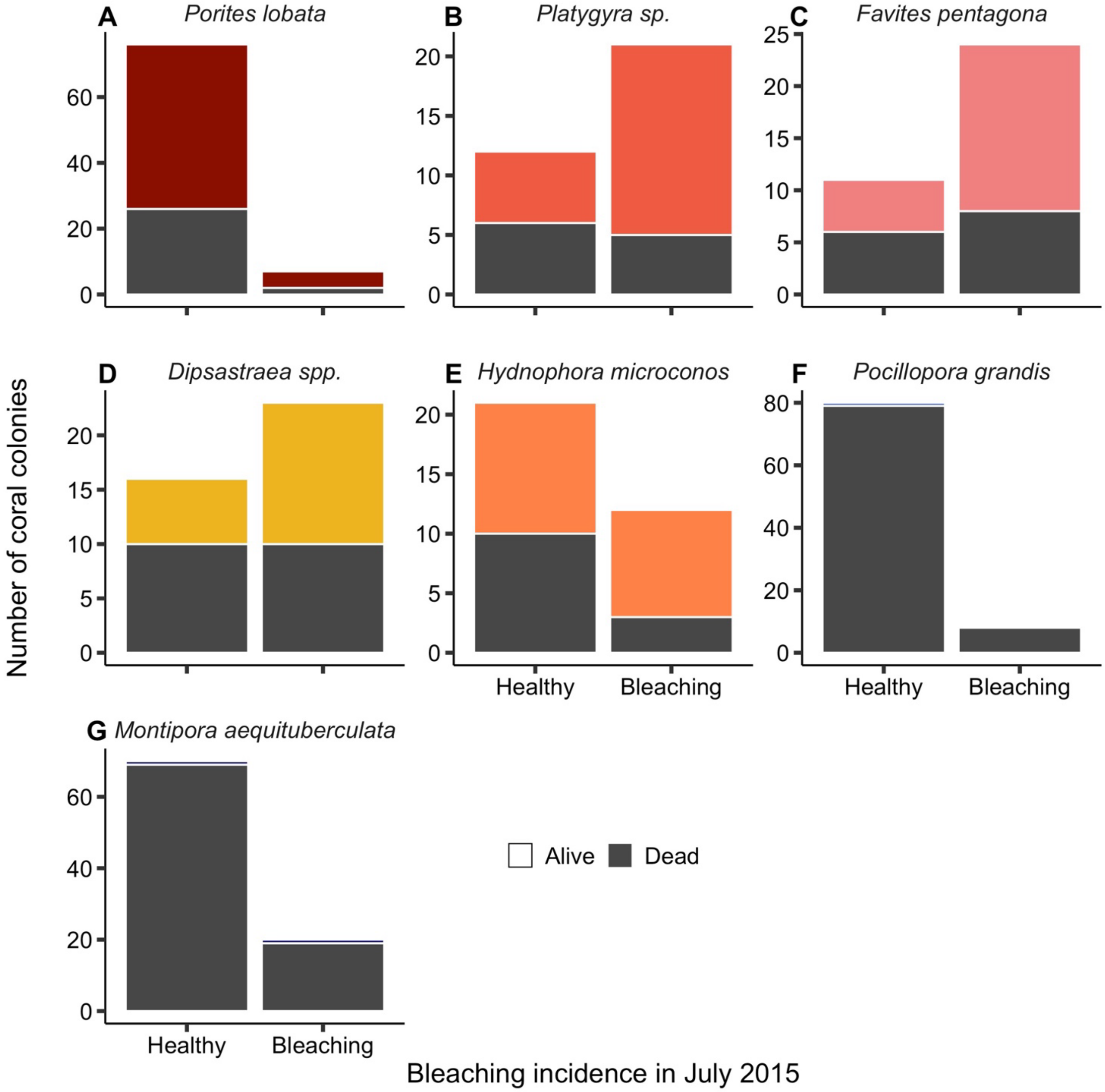

Fig. S13. Survival status of tagged coral colonies that were either bleached or healthy early in the El Niño (July 2015). Dead = grey; Alive = colored (colour-coded as in Fig. 5f and Fig. S10-S12).

Table S1. Chronic local disturbance at each of nineteen monitoring sites on Kiritimati. Population is the number of people residing within 2 km of the site. Fishing pressure is the extracted value from a kernel density function of fishing pressure (*82*). Combined metric is the sum of population and fishing pressure, and sites are ordered from greatest to least disturbance according to this metric. Site numbers and disturbance level colours match those on Fig. S2.

Site	Population	Fishing Pressure	Combined Metric	Human Disturbance Category
VH1	4042	3234	7276	Very High
VH3	3065	2021	5086	Very High
VH2	1223	3638	4861	Very High
H2	458	1617	2075	High
M5	0	1617	1617	Medium
M10	1209	404	1613	Medium
M6	351	1213	1564	Medium
M1	0	1213	1213	Medium
M2	0	1213	1213	Medium
M3	0	1213	1213	Medium
M4	351	809	1160	Medium
L1	0	809	809	Low
L2	0	809	809	Low
L4	0	809	809	Low
L5	0	404	404	Low
VL1	0	11	11	Very Low
VL2	0	11	11	Very Low
VL3	0	11	11	Very Low
VL5	0	11	11	Very Low

Table S2. Oceanographic characteristics of monitoring sites on Kiritimati: Max NPP = maximum net primary productivity (mg C m^{-2} day^{-1}), MMM = maximum monthly mean sea surface temperature (°C), Expos. = Exposure (W = windward; S = sheltered), Wave = mean wave energy (kW m^{-1}). Salinity (ppt), DO = dissolved oxygen (mg L^{-1}), pH, and phosphate (μM) are shown as means (± SE) averaged across measurements taken *in situ* in each expedition. Data sources and collection methods detailed in text. Sites are numbered and colour coded by disturbance level (as in table S1 and Fig. S2).

Site	Max NPP (mg C/(m^{-2} day)	MMM (°C)	Expos.	Wave (kW/m)	Salinity (ppt)	DO (mg/L)	pH	Phosphate (μM)
VH1	1112.00	28.02	S	NA	35.48 ± 0.227	5.788 ± 0.131	7.999 ± 0.015	0.414 ± 0.026
VH3	1097.18	28.02	S	24.95	35.73 ± 0.231	5.595 ± 0.106	7.974 ± 0.049	0.440 ± 0.057
VH2	1158.56	28.02	S	NA	35.65 ± 0.334	5.659 ± 0.055	7.928 ± 0.022	0.545 ± 0.050
H2	1097.18	28.02	S	24.95	35.15 ± 0.175	5.282 ± 0.182	7.988 ± 0.012	0.276
M5	1035.06	28.03	W	25.36	35.37 ± 0.043	5.640	7.997 ± 0.013	0.406 ± 0.012
M10	979.54	28.01	W	26.23	35.32	5.677	7.993	NA
M6	984.27	27.99	S	24.80	35.34 ± 0.175	5.977 ± 0.258	7.891 ± 0.091	0.412 ± 0.412
M1	1077.88	27.99	S	24.82	35.12 ± 0.101	5.973 ± 0.113	7.785 ± 0.130	0.446 ± 0.024
M2	1077.88	27.99	S	24.82	35.28 ± 0.089	5.907 ± 0.124	7.977 ± 0.017	0.492 ± 0.026
M3	1070.26	28.01	S	NA	36.41 ± 0.331	5.842 ± 0.130	7.937 ± 0.015	0.409 ± 0.031
M4	984.27	27.99	S	24.80	36.23 ± 0.772	5.763 ± 0.180	7.954 ± 0.026	0.433 ± 0.038
L1	1035.06	28.03	W	25.36	35.18 ± 0.170	6.192 ± 0.180	8.052 ± 0.026	0.417 ± 0.038
L2	992.54	28.02	W	25.73	35.29 ± 0.258	5.397 ± 0.218	7.936 ± 0.029	0.382 ± 0.382
L4	1126.02	28.01	S	NA	35.35 ± 0.300	5.867 ± 0.242	7.952 ± 0.040	0.448 ± 0084
L5	979.54	28.00	W	26.23	35.27	5.933	7.983	NA
VL1	1003.66	27.96	W	26.41	35.14 ± 0.158	5.718 ± 0.128	7.970 ± 0.029	0.448 ± 0.038
VL2	993.43	27.96	W	NA	35.06 ± 0.148	5.737 ± 0.383	8.013 ± 0.032	0.468 ± 0.052
VL3	1031.55	27.97	S	24.90	35.58 ± 0.693	5.581 ± 0.061	7.938 ± 0.013	0.443 ± 0.036
VL5	1015.12	27.97	W	26.07	35.11	7.000	7.977	0.453

Table S3. Comparison of maximum thermal stress (degree heating weeks) and maximum temperature anomaly (above the mean monthly maximum temperature, MMM) across sites on Kiritimati (from NOAA's CRW product (*94*)) during the 2015–2016 El Niño event.

Site	**Maximum Thermal Stress (degree heating weeks, °C-weeks)**	**Maximum Temperature Anomaly (°C above MMM)**
VH1	24.36	2.86
VH3	24.36	2.86
VH2	24.33	2.87
H2	24.36	2.86
M5	24.26	2.83
M10	24.75	2.92
M6	24.71	2.89
M1	24.71	2.89
M2	24.69	2.90
M3	24.39	2.87
M4	24.71	2.89
L1	24.26	2.83
L2	24.5	2.88
L4	24.39	2.87
L5	24.99	2.94
VL1	25.28	3.04
VL2	25.34	3.05
VL3	25.05	2.95
VL5	25.2	3.02
Mean	**24.67**	**2.91**
Std. Dev.	**0.36**	**0.07**

Table S4. **Results (parameter estimates) for fixed effects from generalized linear models and generalized linear mixed-effects models examining the influence of benthic and environmental variables on hard coral cover** before the heatwave (**A**) and across heatwave periods (**B, C**). Abbreviations: Dist. = local human disturbance; NPP = maximum net primary productivity (mg C m^{-2} day^{-1}); Quad. = quadratic relationship; MMM = maximum monthly mean temperature (°C); Expos. = site exposure; DHW = degree heating weeks (°C-weeks); Comp. = competitive. Bold indicates significant difference from baseline levels (Exposure = Leeward; Heat = Before; Life History = Stress-tolerant) at $\alpha = 0.05$; asterisks indicate levels of significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Red shaded boxes denote variables with significant negative estimates, indicating a decline compared to baseline levels.

A)

Model	**n**	**Dist.**	**NPP**		**MMM**	**Expos.**	**R^2**
			Linear	**Quad.**			
Main model							
Model 1	19	**-1.204****	-1.049	-0.998	0.120	0.033	0.708
Supplementary models							
Model 1a	17	**-1.298*****	**-1.322***	**-1.009***	0.206	-0.101	0.743
Model 1b	39	**-1.610*****	-1.728	**-2.026***	0.144	-0.024	0.826

B)

Model	**n**	**Heat**	**Dist.**	**DHW**		**NPP**		**Heat*Dist.**	**R^2**
				Linear	**Quad.**	**Linear**	**Quad.**		
Main models									
Model 2	38	**-2.688*****	**-1.532*****	-0.230	- - -	-1.832	**-1.968***	**1.440*****	0.898
Model 2c	38	**-4.939*****	**-1.162*****	1.653	1.192	**-0.680***	- - -	**1.877*****	0.965
Model 2s	38	**-1.803*****	**-1.866*****	**-1.046****	- - -	- - -	- - -	**0.802***	0.742
Supplementary models									
Model 2a	35	**-2.746*****	**-1.563*****	-0.311	- - -	-1.985	**-1.847***	**1.512*****	0.914
Model 2ca	35	**-4.894*****	**-1.130*****	1.666	0.740	**-0.724***	- - -	**1.635****	0.966
Model 2sa	35	**-1.859*****	**-1.955*****	**-1.138****	- - -	- - -	- - -	**0.948***	0.757
Model 2b	67	**-2.460*****	**-1.701*****	-0.167	- - -	-2.370	**-2.781***	**1.538*****	0.876
Model 2cb	67	**-3.665*****	**-1.210*****	2.032	**1.683***	**-0.586***	- - -	**2.089*****	0.941
Model 2sb	67	**-1.665*****	**-2.300*****	**-1.006****	- - -	- - -	- - -	**0.908*****	0.701

C)

Model	**n**	**Heat**	**Life History**		**DHW**	**NPP**		**Heat*Life History**		**R^2**
			Comp.	**Mixed**		**Linear**	**Quad.**	**Comp.**	**Mixed**	
Main model										
Model 3	38	**-2.492*****	-0.739	0.0003	0.681	**-3.018****	**-2.664****	**-0.914***	-0.545	0.912
Supplementary models										
Model 3a	35	**-2.617*****	**-0.784***	-0.031	0.641	**-2.973****	**-2.480****	-0.673	-0.438	0.932
Model 3b	67	**-2.394*****	**-0.928***	-0.025	**0.795***	**-4.071****	**-3.735****	**-0.952****	-0.588	0.887

Note: Models were fit using three different data sets: *Main models* include data from all expeditions conducted during the 'before' and 'after' heatwave periods, with data points averaged across expeditions to produce one point per site per heatwave period (n = 19 data points **[A]**, 38 data points **[B, C]**); *Supplementary models* denoted 'a' include only the data from the largest sampling event in each heatwave period (July 2013 for the 'before' period and July 2017 for the 'after' period) (n = 17 data points **[A]**, 35 data points **[B, C]**); those denoted 'b' include data from all expeditions conducted during the 'before' and 'after' heatwave periods (not averaged across expeditions), such that some sites had more than one point per site per heatwave period (n = 39 data points **[A]**, 67 data points **[B, C]**). R^2 values given for all models are marginal R^2 values, which only account for variation explained by the fixed effects.

Model structures are as follows:
A) Model 1: Overall coral cover ~ Disturbance + NPP + NPP^2 + MMM + Exposure
B) Model 2: Overall coral cover ~ Heat * Disturbance + DHW + NPP + NPP^2
Model 2c: Competitive coral cover ~ Heat * Disturbance + DHW + DHW^2 + NPP
Model 2s: Stress-tolerant coral cover ~ Heat * Disturbance + DHW
C) Model 3: Overall coral cover ~ Heat * Life history + DHW + NPP + NPP^2

Table S5. Model results (parameter estimates) from logistic regression models examining influences of survival on tagged coral colonies. Bold indicates significant difference from baseline levels (i.e., stress-tolerant, *Porites lobata*) at α = 0.05; asterisks indicate levels of significance (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). Red shaded boxes denote variables with negative estimates, indicating a decline compared to baseline levels.

		Overall Model	Life History Model	Species Model
Human Disturbance	Continuous	**-0.45716 ± 0.09852*** **	**-1.1749 ± 0.2056*** **	**-1.0410 ± 0.3489** **
Life History	Competitive	- - -	**-4.5880 ± 0.5354*** **	- - -
Disturbance x Life History		- - -	**1.7252 ± 0.6352** **	- - -
Coral Species	*Platygyra ryukyuensis*	- - -	- - -	0.8934 ± 0.6365
	F. pentagona	- - -	- - -	-0.1948 ± 0.4549
	Dipsastraea spp.	- - -	- - -	-0.6015 ± 0.4054
	H. microconos	- - -	- - -	**-0.9001 ± 0.4021* **
	P. grandis	- - -	- - -	**-5.1228 ± 0.8778*** **
	M. aequituberculata	- - -	- - -	**-4.5906 ± 0.6967*** **
Disturbance x species	*Platygyra ryukyuensis*	- - -	- - -	**-1.7636 ± 0.8692* **
	F. pentagona	- - -	- - -	0.2118 ± 0.5741
	Dipsastraea spp.	- - -	- - -	-0.3640 ± 0.6240
	H. microconos	- - -	- - -	0.4780 ± 0.6565
	P. grandis	- - -	- - -	1.8423 ± 0.9944
	M. aequituberculata	- - -	- - -	1.3952 ± 0.8632

Table S6. Coral taxa on Kiritimati. Corals are categorized by the fifteen most common taxa identified in the photoquadrat images (processed using CoralNet) across the n = 19 study sides prior to the 2015–2016 El Niño, and other rarer species. The fifteen most common corals are ordered from most to least common before the El Niño and their rank and proportion after the El Niño is also given. Coral life history strategy retrieved from the Coral Traits Database release 1.1.1 (https://coraltraits.org/) (*88*), unless otherwise noted. Current taxonomy (and name synonymy) retrieved from WoRMS (http://www.marinespecies.org/).

Life History	Family	Species	Notes	Rank and Proportion After
Top 15 most common coral taxa[*]				
Stress-tolerant	Poritidae	*Porites lobata*	May include *P. evermannii* and *P. lutea*	1 (51.4%)
Competitive	Acroporidae	*Montipora aequituberculata*	*M. aequituberculata* with foliose morphology	Tied 14 (0%)
Competitive	Acroporidae	*Montipora* spp.	*Montipora* spp. with encrusting morphology, includes *M. aequituberculata* and a few potentially unnamed species	13 (0.3%)
Competitive	Pocilloporidae	*Pocillopora grandis*	Synonym: *Pocillopora eydouxi*	6 (3.4%)
Stress-tolerant	Merulinidae	*Hydnophora microconos*		5 (3.6%)
Stress-tolerant	Merulinidae	*Dipsastraea matthaii*	Synonym: *Favia matthaii*	8 (3.0%)
Competitive	Pocilloporidae	*Pocillopora meandrina*		10 (1.4%)
Stress-tolerant	Merulinidae	*Goniastrea stelligera*	Synonym: *Favia stelligera*	3 (9.9%)
Stress-tolerant	Agariciidae	*Pavona varians*		11 (1.3%)
Competitive	Acroporidae	*Acropora hyacinthus*	Tabulate morphology	Tied 14 (0%)
Stress-tolerant	Merulinidae	*Platygyra* spp.	Primarily *P. ryukyuensis*, may include *P. contorta*, *P. daedalea*, *P. sinensis*	2 (10.6%)
Weedy	Faviidae (synonym: Incertae sedis)	*Leptastrea* spp.	Includes *L. pruinosa and L. bewickensis*	9 (2.9%)
Stress-tolerant	Acroporidae	*Astreopora* spp.	Includes *A. cucullata, A. myriophthalma*, and *A. suggesta*	12 (1.2%)
Stress-tolerant	Merulinidae	*Favites pentagona*		4 (4.0%)

Stress-tolerant	Agariciidae	*Pavona duerdeni*		7 (3.1%)
Other coral taxa[*] (i.e., Rare species)				**3.9%**
Competitive	Acroporidae	*Acropora* spp.	Corymbose morphology (*A. rosaria*, synonym: *A. loripes*; *A. subulata*; and hybrids of these species)	
Competitive	Acroporidae	*Acropora* spp.	Includes digitate morphology (*A. digitifera*) and any species in the genus *Acropora* that could only be identified to genus. This was often the case with coral recruits that had not yet developed distinguishing morphological characteristics.	
Competitive[†]	Dendrophylliidae	*Turbinaria reniformis*		
Competitive[‡]	Pocilloporidae	*Pocillopora zelli*	Includes *P. zelli* and also *Pocillopora* spp. recruits that could not be identified to species (likely includes *P. meandrina* and *P. grandis* recruits).	
Stress-tolerant	Agariciidae	*Gardineroseris planulata*		
Stress-tolerant[§]	Agariciidae	*Leptoseris mycetoseroides*		
Stress-tolerant	Fungiidae	*Fungia* spp. (also *Lithophyllon* sp., *Danafungia* spp., *Pleuractis* sp., and *Lobactis* sp.)	Includes *F. concinna* (synonym: *Lithophyllon concinna*), *F. corona* (synonym: *Danafungia scruposa*), *F. danai* (synonym: *D. horrida*), *F. granulosa* (synonym: *Pleuractis granulosa), F. scutaria* (synonym: *Lobactis scutaria*)	
Stress-tolerant[‖]	Fungiidae	*Herpolitha limax*		
Stress-tolerant[¶]	Fungiidae	*Sandalolitha robusta*		

Stress-tolerant[#]	Lobophylliidae	*Lobophyllia hemprichii*	
Stress-tolerant	Merulinidae	*Dipsastraea speciosa*	Synonym: *Favia speciosa*
Stress-tolerant	Merulinidae	*Astrea* spp. (synonym: *Montastraea* spp.)	May include *A. annuligera* (synonym: *Montastraea annuligera*), *A. curta* (synonym: *M. curta*)
Stress-tolerant	Merulinidae	*Favites halicora*	
Generalist	Merulinidae	*Hydnophora exesa*	

* Coral taxa included in the top fifteen comprised between 8.32% (*Porites lobata*) and 1% (0.97%; *Acropora* corymbose) of total hard coral cover prior to the El Niño, with the remaining ‘Other’ coral taxa each comprising less than 1% of total hard coral cover.

† Life history strategy extracted from congeneric *Turbinaria mesenterina*

‡ Life history strategy extracted from congeneric *Pocillopora eydouxi*

§ Life history strategy extracted from family Agariciidae (i.e., *Gardineroseris* and *Pavona*)

|| Life history strategy extracted from family Fungiidae (i.e., *Fungia*)

¶ Life history strategy extracted from family Fungiidae (i.e., *Fungia*)

\# Life history strategy extracted from congenerics *Lobophyllia corymbosa* and *Lobophyllia pachysepta*

Table S7. Number of small benthic photoquadrats (PQs) photographed per disturbance level on Kiritimati in each of nine expeditions straddling the 2015–2016 El Niño: four before (2013–2015), three during (2015–2016) and two after (2016–2017) the event. Numbers in parentheses indicate the number of different sites that the PQs were photographed at in each disturbance level on each expedition.

Disturbance Level	**Before El Niño**				**During El Niño**			**After El Niño**		**Total PQs per Disturbance Level**
	Jul 2013	Aug 2014	Jan 2015	May 2015	Jul 2015	Nov 2015	Mar 2016	Nov 2016	Jul 2017	
Very Low	73 (3)	0	28 (1)	44 (2)	87 (3)	0	59 (2)	60 (2)	102 (4)	**453**
Low	78 (3)	63 (2)	0	0	60 (2)	0	59 (2)	0	88 (3)	**348**
Medium	177 (7)	135 (5)	60 (2)	90 (3)	149 (5)	36 (2)	102 (4)	120 (4)	193 (7)	**1,062**
High	30 (1)	0	0	0	0	0	0	0	30 (1)	**60**
Very High	87 (3)	55 (2)	60 (2)	90 (3)	89 (3)	64 (2)	90 (3)	90 (3)	89 (3)	**714**
Total PQs (Sites) per Expedition	**445 (17)**	**253 (9)**	**148 (5)**	**224 (8)**	**385 (13)**	**100 (4)**	**310 (11)**	**270 (9)**	**502 (18)**	**2,637**

Table S8. Number of small benthic photoquadrats (PQs) photographed per site on Kiritimati in each of nine expeditions straddling the 2015-2016 El Niño: four before (2013–2015), three during (2015–2016) and two after (2016–2017) the event.

Disturbance Level	**Site**	**Before El Niño**				**During El Niño**			**After El Niño**		**Total PQs per site**	**Total PQs per Disturbance Level**
		Jul 2013	Aug 2014	Jan 2015	May 2015	Jul 2015	Nov 2015	Mar 2016	Nov 2016	Jul 2017		
Very Low	VL1	23		28	15	29		29	30	30	**184**	**453**
	VL2	20				28				26	**74**	
	VL3				29	30		30	30	27	**146**	
	VL5	30								19	**49**	
Low	L1	28	32			30				29	**119**	**348**
	L2		31			30		29			**90**	
	L4	25						30		30	**85**	
	L5	25								29	**54**	
Medium	M1	29	27	30	30	30	27	30	30	29	**262**	**1,062**
	M2	26	31	30	30	29	9	26	30	29	**240**	
	M3	28	31		30	29		30	30	29	**207**	
	M4	13	21			30		16		30	**110**	
	M5	25	25			31				17	**98**	
	M6	28					30			30	**88**	
	M10	28								29	**57**	
High	H2	30								30	**60**	**60**
Very High	VH1	28	30	30	30	29	30	30	30	29	**266**	**714**
	VH2	30			30	30	34	30	30	30	**214**	
	VH3	29	25	30	30	30		30	30	30	**234**	
Total PQs per Expedition		**445**	**253**	**148**	**224**	**385**	**100**	**310**	**270**	**502**	**2,637**	

Table S9. Number of tagged individual coral colonies of each species with known survivorship status, categorized by disturbance level. Species are ordered from highest to lowest sample size.

	Disturbance Level				
Species	Very Low	Low	Medium	Very High	**Species Totals**
Competitive Life History Strategy					
Montipora aequituberculata	35	8	33	25	101
Pocillopora grandis	34	12	35	19	100
Stress-Tolerant Life History Strategy					
Porites lobata	32	8	38	21	99
Dipsastraea spp. *(D. matthaii)*	6	7	24	16	53
Hydnophora microconos	13	6	15	7	41
Platygyra ryukyuensis	12	4	13	11	40
Favites pentagona	12	4	11	13	40
Totals	**144**	**49**	**169**	**112**	**474**

Supplementary_Data_1.xlsx (separate file)
Data for literature review examining studies assessing impacts of marine heatwaves between 2014 to 2021 on corals and whether each study also quantified the effects of local anthropogenic disturbance.

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