**Coral resilience to unprecedented heat stress**

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**Summary**

**Main text**

Global coral bleaching is increasing, and the 2014-2017 event caused a catastrophic loss of corals around the globe. WHAT IS CORAL BLEACHING. The 2014-2017 global coral bleaching event caused coral bleaching across the world's oceans (Eakin 2016, Normile 2016), with up to 75% bleaching on some reefs in Hawaii, and at least some level sof bleaching across 93% of the Great Barrier Reef (Minton et al 2015, GBRMPA 2016). The 2015-2016 El Niño, superimposed on nearly-ubiquitous tropical ocean warming, instigated the third global coral bleaching event (@Eakin:2016vf). Despite staggering losses caused by ocean warming at a global scale, some corals have the capacity to be resilient to increasingly frequent mass-bleaching events (Hughes et al 2017).

The symbiosis between coral and their single-celled photosynthetic dinoflagellate symbionts, *Symbiodinium*, is the foundation of coral reef ecosystems, supporting reef diversity and function at a global scale. There is much genetic, functional, and response diversity within the genus *Symbiodinium*. The *Symbiodinium* genus is divided into nine functionally distinct clades [@Stat2008-hk], and *Symbiodinium* associations can range from mutualistic to neutral to parasitic based on *Symbiodinium* type as well as environmental conditions [@Lesser2013-dj]. *Symbiodinium* types (a subdivision of clades), considered putative species [@Pochon2010-jm], have distinct geographic distributions, host associations, and environmental optima [@Fabina2012-mm]. NON SEQUITIR HERE… Recent advances in next-generation sequencing techniques have revealed cryptic genetic diversity within symbiotic *Symbiodinium* [@Quigley2014-zj; @Arif2014-kx; @Green2014-az], and has allowed for long-term genetic and ecological comparisons of symbiont community structure [@Edmunds\_undated-fd].

STILL NOT A SMOOTH TRANSITION HERE. Here we show that despite the unprecedented heat stress that occurred during the 2015-2016 El Niño event, some corals exhibited resilience and survived (Figure 1). Our study location, Kiritimati Atoll (Christmas Island, Kiribati, Central Equatorial Pacific, Coordinates: 2.0, -157.4), was at the epicenter of this extreme El Niño event. Thermal anomalies were severe on Kiritimati, rapidly exceeding NOAA Coral Reef Watch's Coral Bleaching Alert Level 1 and Alert Level 2 thresholds, reaching an unprecedented (@Hoegh-Guldberg2011-sl) 25.7 DHW over a year-long bleaching event, demolishing most of the reef (Figure 1a, @Baum\_inprep). Here, we assess coral symbiosis and survival during the massive 2015/2016 El Niño event. We tagged, sampled, and photographed the same coral colonies before, during, and immediately after the El Niño event. We determined bleaching condition and survival for each coral colony, and used Illumina MiSeq ITS2 amplicon sequencing and 97% \*de novo\* OTU clustering to evaluate changes in *Symbiodinium* community structure. To investigate mechanisms underlying the ability of these corals to not only survive a year of continuous heat stress, but to recover in the interim, we assessed the relationship between human disturbance, pre-bleaching *Symbiodinium* community structure, and coral survival, as well as the timing of *Symbiodinium* community shifts throughout this El Niño event.

The current paradigm of coral bleaching and resilience is that as environmental stress (such as warming) increases, corals begin to lose their obligate symbionts (*Symbiodinium*) and "bleach" [@Gates1992-ew; @Douglas2003-nr]. Thermal stress is the primary cause for coral bleaching, and extreme or long-lasting warming causes a complete breakdown of symbiosis, leading to expulsion of all (or nearly all) *Symbiodinium* from the coral host tissue, often leading to coral mortality [@Hoegh-Guldberg1999-rb]. During bleaching, there is a window for recovery, that is, a certain amount of time during which the warming must cease and conditions must return to normal so that the coral can regain its symbionts. If the window for recovery passes without amelioration of environmental conditions, the coral will starve and die. (Cunning et al 2016, Putnam et al 2017). NEED BETTER SEGUE HERE Survival through such an extreme heat event provides an exceptional opportunity to understand how some corals can withstand intense heat stress, and how corals in general might survive long-term warming. Remarkably, we find that some coral colonies were able to survive this prolonged heat stress by regaining their symbionts after XX months of heat stress while temperatures were still elevated. Here, we provide the first evidence that corals have the capacity to not only survive, but to regain their symbionts and visibly recover from bleaching while still under intense thermal stress (Figure 1b, 2ab). These corals (Scleractinia family Merulinidae; *Platygyra* sp. and *Favites* *pentagona*) were bleached within two months of the onset of warming, but had visibly recovered after 10 consecutive months of intense warming (Fig. 1).WRAP UP AND TIE TO SYMBIO COMMUNITY?

It is thought that corals may be able to survive thermal stress by changing their complement of symbionts to better suit environmental conditions. The adaptive bleaching hypothesis suggests that corals bleach to expel environmentally sub-optimal symbionts, followed by switching (picking up new symbionts from the environment) or shuffling (an internal change in dominant symbiont type or overall symbiont community structure) [@Buddemeier2004-se; @Buddemeier1993-sx; @Baker2001-vc; @Baker2003-ks]. There is evidence for both *Symbiodinium* shuffling (Rowan 2004) and switching [@Boulotte2016-dy]. However, what remains unclear is if and how frequently bleaching events can actually be considered adaptive. Changes in symbiotic function ARE THESE + or - ? have been demonstrated due to shifts in the dominant *Symbiodinium* clade CAN I SAY SUCH AS C TO D?, and functional differences such as photosynthetic efficiency and bleaching resistance are also present among *Symbiodinium* types within a single clade [@Sampayo2008-tw; @Kemp2014-xj]. Clade D *Symbiodinium* are considered heat-tolerant symbionts [@Stat2010-zg]. Furthermore, repopulation of a coral host with clade D symbionts after a bleaching event is proposed to be a survival mechanism [@Berkelmans2006-rf; @Mieog2007-yy; @Silverstein2012-tm]. For example, one study showed that a history of thermal stress increased the prevalence of clade D *Symbiodinium* in one coral species, but did not instigate similar changes in two other coral species [@Stat2013-qp]. However, there is a trade-off to housing Clade D *Symbiodinium*, as corals that house clade D symbionts may have slower growth rates [@Little2004-tm] or lower capacity for energy storage [@Jones2011-nf]. WHAT WE FOUND FOR C VS D

Stochasticity in the rare *Symbiodinium* biosphere may build or weaken a coral's capacity for resilience. Corals commonly host background *Symbiodinium* types in low levels (Correa et al 2009), but sub-dominant *Symbiodinium* communities are often unstable (Coffroth et al 2010). Despite their small numbers, rare microbial species have been demonstrated to be disproportionally important to maintaining functional processes during environmental change in other systems (Shade et al 2014). The importance of rare *Symbiodinium* types is currently under debate, and these rare types may be commensal (symbionts that pass through with no harm or gain for either partner), parasitic ("cheaters" (Yu 2001), or opportunistic symbionts that take more than they give), or mutualistic (symbionts which support host function) (Parkinson et al 2015). Some research suggests that low-abundance *Symbiodinium* types have minimal functional significance to corals (Lee et al 2016), while other evidence supports the idea that shifts in *Symbiodinium* community diversity may have a large influence on coral resilience (Baskett et al 2010), and that the rare *Symbiodinium* biosphere is important for corals' response to climate change (Boulotte et al 2016). We show that after two months of heat stress, fully-bleached corals retained approximately the same *Symbiodinium* community as they had before the bleaching event (Figure 2a). This suggests that a wholesale breakdown of symbiosis occurred in bleached corals during this event, indicating a lack of preferential symbiont expulsion or exodus. Furthermore, some coral colonies changed *Symbiodinium* communities drastically upon recovery, and recovered symbiosis with *Symbiodinium* types that were present in only a negligible amount before the bleaching event (Figure 2b). This supports recent evidence suggesting that symbionts present in even very low abundances can play a critical role in coral survival and recovery (CITE recent papers).

Global climate change is superimposed on a suite of local stressors on coral reefs ranging from overfishing to pollution. Coral reef management has typically focused on minimizing local stressors, through marine protected areas that restrict fishing pressure or limiting agricultural runoff and sewage inputs, rather than attempting to directly mitigate underlying climate stressorsbut see vanOppen et al. 2015 PNASetc.etc. Local management measures can significantly enhance reef recovery rates following bleaching events, for example, by protecting populations of herbivorous fishes which indirectly provision space for new coral recruits by mediating competition between coral and macroalgae. What is unclear is if local management can also influence coral resistance to heat stress, and if so via which mechanisms. Coral bleaching and mortality on the Great Barrier Reef during the 2015-2016 El Niño event occurred irrespective of local protection, with no detectable differences across water quality or fishing pressure levelsHughes et al. 2017. –plus Emily’s paper showing protection in Kenya didn’t matter either –describe other studies that may have provided evidence that local protection does enhance resistance (Carilli? Etc) – but the mechanism was still unknown. –then a sentence describing what is known about how local protection influences *Symbiodinium* communities. –then BOOM! Our findings (evidence PLUS the mechanism because we rock)!!!

Notes:

-it has been unclear via what mechanism local protection would enhance coral resistance to heat stress – Here, we show that it does enhance coral resistance to heat stress \*\*AND\*\* we show the mechanism of how it does so.

-~90% mortality on KI (cite bleaching paper), but different mortality for some species

We show that corals living at different levels of local human disturbance had distinct symbiont communities that corresponded tightly to survivorship. This is in contrast to a recent study which concluded that particulate and dissolved nutrients do not reduce coral health at a colony scale (Rocker et al 2017).

There is increasing evidence for local adaptation in corals (Howells et al 2012, Logan et al 2013, Dixon et al 2015). Our results suggest that some coral species may have the capacity to experience evolutionary rescue, defined as adaptation at a rate that allows an endangered population to survive the rate of environmental change (Orr & Unkless 2014, Carlson 2014). Our results suggest that the capacity for evolutionary rescue is tangibly related to local reef protection. Although massive bleaching events like this one will likely continue to cause catastrophic damage to coral reefs worldwide, mitigating local human disturbance can potentially help protect some coral species against a modest amount of ocean warming.

Methods

Study Location

Kiritimati Atoll (Christmas Island), Kiribati is located in the Central Equatorial Pacific (1.9N 157W), at the center of the El Niño 3.4 region (a region which is used to quantify El Niño presence and strength). During the 2015/2016 El Niño event, Kiritimati experienced 10 months of sustained temperature stress, causing a mass bleaching and mortality event (@BauminPrep).

Temperature quantification

Temperature loggers (SBE 56, Sea-Bird Scientific) were deployed around the island at 10-12m depth from 2011-2016 to measure \*in situ\* thermal stress.

Coral Tagging and sampling

In August/September 2014, XX colonies of \*Platygyra\* sp. and \*Favites pentagona\* were tagged along a 60m transect at 10-12m depth at 15 different sites around Kiritimati atoll. A photo was taken of each coral to record colony measurements and bleaching. The tagged coral colonies were resampled twice more before (January/February 2015, April/May 2015), once during (July 2015), and once near the end (March 2016) of the El Niño warming. Some tagged coral colonies were lost due to storm damage, and new coral colonies were tagged to replenish the total number of surveyed colonies. Not all sites were visited during all field seasons, and some site surveys were only partially completed during some field seasons due to inclement weather conditions. Corals were sampled underwater using a small chisel, and stored in seawater on ice until preservation. Coral tissue samples were preserved in Guanidinium buffer (50% w/v guanidinium isothiocyanate; 50 mM Tris pH 7.6; 10 µM EDTA; 4.2% w/v sarkosyl; 2.1% v/v-mercaptoethanol) and stored at 4 \*degrees\* until extraction.

Sample processing and sequencing

DNA extraction was performed using a guanidinium-based extraction protocol [@Stat2009-qq; Cunning2017-sc; Cunning2015-mt] with the modification that the DNA pellet was washed with 70% ethanol three times rather than once. After extraction, DNA was cleaned using Zymo Genomic DNA Clean and ConcentratorTM -25 (Catalog Nos. D4064 & D4065) following the standard protocol (<http://www.zymoresearch.com/downloads/dl/file/id/638/d4064i.pdf>). DNA was measured using the dsDNA Qubit BR assay. Any samples that had concentrations below detection levels of this assay, were quantified using the dsDNA Qubit HS assay.

Library preparation for Illumina MiSeq sequencing was performed following the Illumina 16S Metagenomic Sequencing Library Preparation (Illumina protocol, Part # 15044223 Rev. B) with the following modifications:

* ITS primers (ITS-forward: 5’-TCG TCG GCA GCG TCA GAT GTG TAT AAG AGA CAG GTG AAT TGC AGA ACT CCG TC-3’ and ITS-reverse: 5’-GTC TCG TGG GCT CGG AGA TGT GTA TAA GAG ACA GCC TCC GCT TAC TTA TAT GCT T-3’ [@Stat2009-qq]) were used instead of the 16S primers
* PCR 1 annealing temp was 52°C, PCR 1 was performed in triplicate, and PCR product was pooled prior to bead clean.
* 60 µl SPRI beads were used for PCR 1 clean up
* PCR 1 bead clean up elution buffer volume varied depending on the Qubit concentration of initial gDNA. Changes were as follows:
  + gDNA concentrations with 1 ng/ µl (or less) were resuspended in 12.5 µl elution buffer
  + gDNA concentrations between 2 ng/ µl to 4 ng/ µl were resuspended in 42.5 µl elution buffer
  + gDNA concentrations of 5 ng/ µl were resuspended in 52.5 µl elution buffer

Samples were sequenced on the Illumina MiSeq platform with 2x300 paired-end read chemistry. A total of 289 samples were prepared for sequencing, and \*XXXX\* of these samples were successfully amplified, sequenced, and used in downstream analyses.

## Bioinformatics

We conducted quality filtering of raw reads (in .fastq format) first using the iu-filter-quality-bokulich script implemented in Illumina-Utils [@Bokulich2013-cm; Eren2013-yg], followed by paired-end sequence merging via the iu-merge-pairs script (also in Illumina-Utils, [Eren2013-yg]), with a maximum mismatch of three bases between the forward and reverse reads. After quality filtering, sequence processing and identification was performed following all specifications of [@Cunning2017-sc]; chimeric sequences were removed, primers were trimmed, sequences from each sample were clustered independently at 97% similarity using UCLUST [@Edgar2010-zl] implemented in QIIME [@Caporaso2010-yl] and resulting OTUs were collapsed at 100% identity across samples, sequences were aligned using the Needleman-Wunsch global alignment algorithm (Biostrings package, [@Pages2017-ie]) in R [@R\_Development\_Core\_Team2008-sp], and sequences were named using a reference database.

The Phyloseq package [@McMurdie2013-hf] in R was used to store and analyze OTU tables, taxonomic information, and sample metadata. The phyloseq object was filtered to remove OTUs observed <10 times (n=\*83\* OTUs removed and n=\*81\* kept). The phyloseq object was further filtered to remove samples with very low sequence abundances due to amplification issues (<200 sequences, n=\*27\* samples removed and n=\*262\* kept).

In \*262\* coral samples, we found XXXX sequences after quality filtering. \*clade abundances here\*

## Statistical Analysis

Code will be avaible on git hub

CAP – constrained ordination methods

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**Author Information**: The authors declare no competing financial interests.

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**Figure 1 | Thermal stress experienced by corals, and the transition of one such coral from healthy – bleached – recovered, at the epicentre of the 2015-2016 El Niño event. a.** Degree Heating Weeks (DHW), on Kiritimati Island over the course of the 2015-2016 El Niño event. Corals are sensitive to temperatures warmer than 1°C above their normal highest summertime mean sea surface temperature (SST), known as the bleaching threshold. DHW shows how much heat stress has accumulated in an area over the past twelve weeks by summing any temperature exceeding the bleaching threshold during that period. Horizontal lines show expected bleaching severity levels: 4°C (yellow line), NOAA Coral Reef Watch (CRW) Bleaching Alert Level 1 (significant bleaching likely); 8°C (light orange line), Bleaching Alert Level 2 (widespread bleaching and mortality may occur); 12°C (dark orange line), ‘mass coral mortality’ expected to occur (Hoegh-Guldberg 2011); 24°C (dark red line) ‘not experienced by reefs yet’ (Hoegh-Guldberg 2011). Solid black line indicates *in situ* calculated DHW, and fill colors correspond to bleaching severity levels. Dashed vertical gray lines show the six sampling time points. **b.** Photographs of the same tagged *Platygyra* coral colony (#99), from the six time points (dashed grey lines), showing the initially healthy colony (i-ii) bleached after two months of heat stress (iv), ‘recovered’ to a normal brown colour after ten months of heat stress (v), and still alive six months post heat stress (vi).

**[input figure 2 file here when we are ready to submit]**

**Figure 2 | Shift in *Symbiodinium* community composition from clade C to clade D dominance over the course of the 2015-2016 El Niño.** *Symbiodinium* community composition at each of five sampled time points for **i)** the entire pool of tagged coral colonies (solid lines, n=21-67 colonies per time point), and **ii)** a single representative tagged *Platygyra* colony (dashed lines).

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Figure 3 Constrained ordination plot showing groupings of *Symbiodinium* communities from individual *Platygyra* colonies, grouping into two distinct areas according to level of local disturbance. Ellipses show separation of the corals which survived the bleaching event (“Alive”, left side of plot) and those that did not (“Dead”, right side of plot). Values on x- and y- axes show per cent variation explained by each constrained axis.

**[insert extended data figure 1 here]**

**Extended Data Figure 1 | Transition of individual tagged coral colonies on Kiritimati Island from bleached – recovered over the course 2015-2016 El Niño event.** Photographs of **i-ii.** *Favites pentagona*, **iii-iv.** *Platygyra* sp., **v-vi.** *Favia matthaii* (*Dipsastrea matthaii*) taken two months into the heat stress (July 2015, left column) and at the conclusion of the heat stress (March 2016, right column), demonstrating the visual recovery of several coral species before the conclusion of the heat stress event.

**Extended Data Figure 2 |** Potentially the rank abundance plot for Platy…..