**Coral And *Symbiodinium*:**

**The Role of Disrupted Nutrient Cycling in Coral Bleaching**

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**Introduction**

The coral reef ecosystem relies on the symbiotic relationship between the coral polyps, dinoflagellate *Symbiodinium*, and coral microbiomes to thrive in nutrient-limited habitats. With *Symbiodinium* performing photosynthesis, microbiomes providing bioavailable nitrogen and phosphorus, and the efficient recycling of nutrients within the ecosystem, the coral reefs support highly diverse and productive biological systems in oligotrophic habitats (Rädecker et al., 2015) – a seeming contradiction that has been termed the *Darwin’s Paradox* (Burkhardt, 1984; de Goeij et al., 2013). Despite coral’s adaptability to limited nutrients, massive coral bleaching can happen with sustained (1-2 months) temperatures of only 1–2°C above the average annual maxima (Goreau and Hayes, 2021; Smith et al., 2017). Heat waves led to massive coral bleaching events in the summers of 1998, 2005, 2010, and 2016 (Hughes et al., 2018). Bleaching occurs due to the expulsion of the colorful symbiotic zooxanthellae (Berkelmans and van Oppen, 2006); the prolonged absence of the symbiotic algae leads to the starvation and death of coral hosts. Here, we explore various mechanisms that precipitate bleaching events. We propose that the disruption of nutrient cycling between the *Symbiodinium* and coral hosts under thermal stress is central to bleaching, while nitrogen pollution and ocean acidification have synergistic contributions.

**Nitrogen Enrichment Disrupts Nutrient Cycling**

Elevated temperatures break down the symbiotic nutrient cycling by decreasing the carbon (energy) availability to the host but increasing the nitrogen availability to the Symbiodiniaceae, resulting in bleaching. For coral hosts, high temperatures mean starvation: first, oxygen fluxes measurement suggested that heat stress increases the respiration rate of the coral host (Fig. 1A) (Rädecker et al., 2021). Second, isotopic analysis revealed that heat stress reduced the translocation of photosynthates from the symbiotic algae to hosts (Fig. 1B, 1C, 1D) (Béraud et al., 2013; Rädecker et al., 2021). Transcriptomes of heat-treated coral hosts affirmed their starvation status (Rädecker et al., 2021). Unlike their starving hosts, many *Symbiodinium* strains maintain a near-optimal cell density (Díaz-Almeyda et al., 2017; Goulet et al., 2017) and photosynthesis efficiency (Takahashi et al., 2013; Xiao et al., 2022) when they are under the temperature threshold of coral bleaching.

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**Fig. 1** Starvation of coral hosts after 10 days of heat stress. **(A)** Respiratory carbon consumption of the holobiont derived from oxygen fluxes. Pale bars are carbon demand fulfilled by gross photosynthetic production. **(B)** Assimilation of 13C-bicarbonate (H13CO3−) into coral host and algal symbiont cells, based on NanoSIMS imaging **(C and D)**. \* Represent significant differences (*p* < 0.05). Adapted from Rädecker et al., 2020.

The growth of Symbiodiniaceae is highly dependent on nitrogen availability (Béraud et al., 2013; Falkowski et al., 1993), and warmer water promotes nitrogen assimilation in symbiotic algae in 2 ways. First, coral hosts switch from anabolic (growth) to catabolic activities under starvation, increasing the nitrogen availability within the host cell, where the algae live (Rädecker et al., 2021). Second, high temperature increase the abundance of diazotroph in the bacterial communities in the coral (Santos et al., 2014) (Fig. 2A) and nitrogen fixation rate of microbial nitrogenases (Stal, 2017) (Fig. 2B).

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**Fig. 2 (A)** Relative abundance of nifH versus bacterial 16S rRNA gene (nifH/16S rRNA) copies per ng DNA determined by qPCR. Values: means (± SE) from three replicates. \* Significant different compared to control. Adapted from Santos et al., 2014. **(B)** Total nitrogenase activity (light-dependent + light-independent) of cyanobacterium *Fischerella sp.* at the O2 concentration of 20%. Adapted from Stal, 2017.

Thus, the greater nitrogen availability promotes the growth and division of Symbiodiniaceae, without increasing photosynthate translocation from algae to host (Fig. 1). The selfish photosynthate retention of algae violates the symbiotic relationship, disproportionally distressing coral hosts. Under thermal stress, genes related to stress response and glycogen production were upregulated in only host transcriptomes, but not in the transcriptomes of Symbiodiniaceae (Leggat et al., 2011) (Fig. 3). This differential gene regulation indicates the starvation of coral hosts but a non-stressful environment for Symbiodiniaceae, which is accord with the situation described in the nutrient disruption hypothesis.

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**Fig. 3** Differential gene expression in **(left)** host cells and **(right)** Symbiodiniaceae during a simulated bleaching event (mean ± SE). Host and algae samples were obtained from either control *A. aspera* nubbins or heated *A. aspera* nubbins. Controls (♦) have relative expression values of while heated tanks (▪) are changes in gene expression relative to controls on that day. Error bars represent standard error (n = 6 for each treatment). Adapted from Leggat et al., 2011.

Evidence from multiple angles support the role of nutrient cycling disruption in bleaching. By selecting the fastest replicating lineage under heat stress for generations, Buerger et al. (Buerger et al., 2020) cultivated strains of *Symbiodinium* that make corals more resistant to bleaching. These heat-evolved Symbiodiniaceae have lower secretion of reactive oxidative species (ROS), higher expression of carbon fixation genes, and higher photosynthetic efficiency (Fig. 4). The superior carbon fixation ability of these dinoflagellate symbionts might increase photosynthate production, alleviating host starvation. Regarding nitrogen enrichment, nitrogen pollution sites were strongly associated with bleaching in field studies, independent of temperature (Bell et al., 2014; Donovan et al., 2020; Zhao et al., 2021). In laboratory environments without heat or light stress, bleaching can be replicated by increasing microbial nitrogen fixation with sugar supplement (Pogoreutz et al., 2017). Overall, the disruption of coral nutrient cycling is a result of warming, but it can also cause bleaching independent of temperature.

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**Fig. 4** Heat-evolved Symbiodiniaceae might have higher photosynthate production and lower ROS release. **(A)** Differentially expressed genes coding for Calvin-Benson pathway (FDR < 0.05) in heat-evolved symbionts versus WT1 symbionts. After 21 days of heat stress, **(B)** ∆value differences in algal symbiont strains maximum quantum yield of photosystem II, and **(C)** ROS secreted into culture medium measured in fluorescence and normalized to cell numbers. Gray (box color): heat-evolved strains, blue: wild-type strains. Adapted from Buerger et al.,2020.

**What is the immediate trigger of symbiont expulsion/digestion?**

Coral bleaching is a result of the digestion or expulsion of the algal symbionts (Fujise et al., 2014; Rädecker et al., 2021). Although a disrupted nutrient cycle is detrimental to coral hosts, the mechanism by which it triggers bleaching is under debate. Some hypothesized that the coral host digest its symbiotic algae upon their reduced photosynthate translocation (to the host) in high temperatures, leading to bleaching (Rädecker et al., 2021). Many believes that coral symbiosomes are arrested early phagosomes (Malcolm and April, 2012; Mohamed et al., 2016; Tang, 2015) – engulfed algae disguise as digesting phagosomes by outputting photosynthates and other products (Malcolm and April, 2012; Tang, 2015). As Symbiodiniaceae rapidly divide without emitting sufficient photosynthates, their disguise cannot be maintained, leading to the digestion of Symbiodiniaceae and further starvation of the host (Rädecker et al., 2021). However, Jinkerson et al. (Jinkerson et al., 2022) challenged this hypothesis, showing that Symbiodiniaceae could proliferate and be maintained (for 6 months) in coral *Acropora* without photosynthesis (Fig. 5). Symbiodiniaceae can also form symbiosis relationship with other *Cnidarians*, including *Cassiopeia* (a family of jellyfish) and *Aiptasia* (sea anemone); intriguingly, their symbiosis with both animals only can develop under light (Jinkerson et al., 2022) (Fig. 5). Thus, though the arrested early phagosomes hypothesis might not fully explain bleaching, it provides a new angle to understand bleaching events in jellyfish (McGill and Pomory, 2008) and anemone (Norin et al., 2018).

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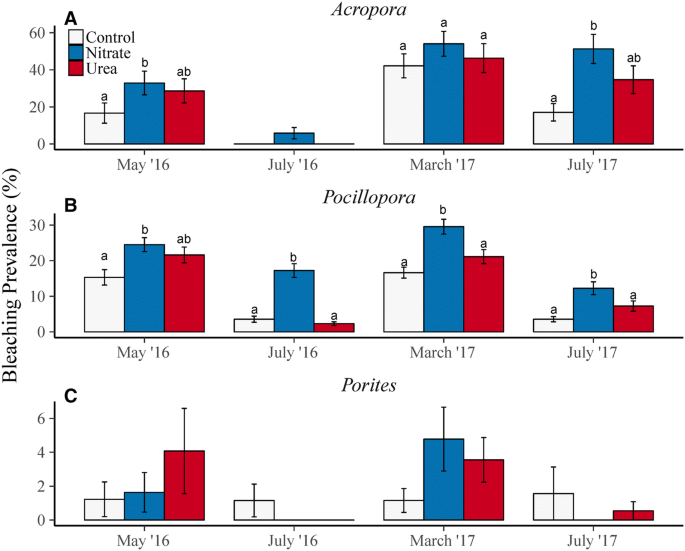
**Fig. 5** Symbiont infection, proliferation, and maintenance are independent of photosynthesis in select cnidarian-Symbiodiniaceaerelationships. With photosynthesis, Symbiodiniaceae proceed through infection, proliferation, and maintenance in hosts (not shown). Without photosynthesis, Symbiodiniaceae still infect sea anemone *Exaiptasia*, the coral *Acropora*, and the jellyfish *Cassiopea*; its proliferation in *Aiptasia* or *Cassiopea* is extremely limited but can occur in the coral; its maintenance within host tissue can occur but depend on the specific host-symbiont relationship. Adapted from Jinkerson et al., 2022.

A prevailing explanation of bleaching is the release of reactive oxygen species (ROS) from symbiotic algae to host cells. It hypothesizes that under heat and photo-oxidative stress, excessive ROS are produced by the algal photosynthesizing apparatus; ROS then diffuse from the symbionts to the hosts, damaging host cells and leading to the expulsion of algae (bleaching) (Lesser, 1997; Weis, 2008). However, although coral-dinoflagellaterelease more ROS under heat stress (Lesser, 1997; Nielsen et al., 2018), recent studies questioned the causal relationship between algal sourced ROS and bleaching: Nielsen et al. (Nielsen et al., 2018) observed that the production of algal ROS under heat stress had little effect on the physiological parameters (e.g., reduced glutathione, ROS-induced lipid peroxidation) of the host cells. Furthermore, Krueger et al. (Krueger et al., 2015) pointed out host antioxidant responses precede the decline in photosynthesis efficiency; with fluorescent labeling, they also found that host antioxidant production is independent from algal symbiont antioxidant productions within the same treatment group (Table 1). These findings cast doubt on whether algal symbiont photosystems are the sole source of ROS, or can ROS from other sources trigger bleaching?

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **Host SOD** | | **Host CAT** | | **Symbiont SOD** | | **Symbiont APX** | | **Light** | **Temperature** |
|  | **28 °C** | **33 °C** | **28 °C** | **33 °C** | **28 °C** | **33 °C** | **28 °C** | **33 °C** |  |  |
| *Acropora millepora* | | | | | | | | | | |
| **Host SOD** | – | – |  |  |  |  |  |  | n.s. | n.s. |
| **Host CAT** | n.s. | − 0.50 | – | – |  |  |  |  | n.s. | n.s. |
| **Symbiont SOD** | 0.51 | n.s. | n.s. | − 0.61 | – | – |  |  | 0.48 | 0.48 |
| **Symbiont APX** | n.s. | n.s. | n.s. | n.s. | 0.71 | n.s. | – | – | 0.49 | 0.49 |
| **Symbiont KatG** | − 0.45 | − 0.53 | n.s. | n.s. | − 0.74 | n.s. | − 0.69 | − 0.54 | n.s. | n.s. |
|  | | | | | | | | | | |
| *Montipora digitata* | | | | | | | | | | |
| **Host SOD** | – | – |  |  |  |  |  |  | n.s. | n.s. |
| **Host CAT** | n.s. | n.s. | – | – |  |  |  |  | n.s. | n.s. |
| **Symbiont SOD** | n.s. | n.s. | n.s. | n.s. | – | – |  |  | n.s. | n.s. |
| **Symbiont APX** | n.s. | n.s. | 0.61 | n.s. | n.s. | 0.46 | – | – | n.s. | n.s. |
| **Symbiont KatG** | n.s. | n.s. | 0.5 | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. | n.s. |

**Table 1** Pearson correlation coefficients (pairwise correlations) of antioxidant enzyme activities in 2 corals species at 28°C and 33°C, over 9 days. **SOD:** superoxide dismutase, **APX:** ascorbate peroxidase, **CAT:** catalase (host only), **KatG** catalase peroxidase (symbiont only). N = 20 per coral and treatment, except for A. millepora at 33 °C, where N = 17. The last 2 columns show enzymatic responses to natural fluctuations in daily mean light and temperature in the control treatment. Only significant correlations (*p* ≤ 0.05) are shown. Adapted from Krueger et al., 2015.

Reactive species and nutrient disruption might work synergistically to result in bleaching. In a disrupted nutrient cycle, the excess nitrogen favors the reduction from nitrate to ammonia, producing reactive nitrogen species (RNS) such as nitric oxide (Hawkins and Davy, 2012). Symbiodiniaceae prefer ammonium (Li et al., 2021) and invest energy to reduce nitrate to ammonium (Burkepile et al., 2020). Experiments have shown that corals exposed to nitrate are more severely bleached compared to those exposed to the same amount of ammonium (Burkepile et al., 2020) (Fig. 6). With similar nitrogen availability, the more severe bleaching in the nitrate-exposed group is due to either RNS production or the algal energy lost during nitrate reduction. Like ROS, RNS damages photosystem II, decreasing the photosynthetic efficiency of Symbiodiniaceae (Hawkins and Davy, 2012). As such, nitrogen surplus and thermal stress both produce reactive species and hinder carbon fixation, exacerbating host starvation. Although nitrogen enrichment and thermal stress have composite effects on bleaching, we do not know how much effects came from oxidative stress versus host starvation, and the answer might vary across different combinations of different coral and symbiont species. Overall, the immediate trigger for the starving coral host to expel or digest their symbiotic algae is still under active research.



**Fig. 6** Prevalence of bleaching for **(A)** *Acropora*, **(B)** *Pocillopora*, or **(C)** *Porites* corals in the different nitrogen treatments across bleaching surveys in 2016–17. Prevalence was calculated as the percent of the number of individuals of each coral taxon per replicate of each nutrient treatment that exhibited any level of bleaching. Letters above bars denote significant differences among nitrogen treatments. No letters mean no differences among treatments. Data are means ± SE. Adapted from Burkepile et al., 2020.

**Challenges From Ocean Acidification**

Ocean acidification (OA) – caused by a high-level of dissolved CO2 – is a corollary of climate change. OA has been widely observed to decrease coral productivity (daily photosynthesis output minus respiration consumption), independent of temperature (Anthony et al., 2008; Noonan and Fabricius, 2015). Intriguingly, transcriptomes of in hospite Symbiodiniaceae revealed that acidification stress induces minimal responses compared to heat stress, with only a few regulatory changes on genes related to photosynthesis (Davies et al., 2018). When raised in free-living conditions, multiple *Symbiodinium* strains maintain a normal, or even faster, growth rate under doubled concentration of dissolved CO2 (Davies et al., 2018). Currently, there is not conclusive evidence to conclude that OA reduces the photosynthate translocation by Symbiodiniaceae. However, high CO2 levels increase metabolic demands of the coral hosts (Evans et al., 2017) – part of the energy is spent on regulating cellular pH in an acidified environment (Liao et al., 2019; Vidal-Dupiol et al., 2013). While OA may not substantially reduce the productivity of algal symbionts, it disrupts the nutrient balance in corals by increasing coral hosts’ demand for energy. Furthermore, OA suppresses coral growth by hindering calcification and damaging the structural integrity of coral colonies (Anthony et al., 2008; Mollica et al., 2018). This is a reminder that in addition to the well-being of the symbiotic algae and a functioning symbiosis between coral hosts and symbionts, coral conservation faces many challenges including, but not limited to, structural erosion, infectious diseases, and human pollution.

**Timeline

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**Fig. 7** Schematic of coral bleaching due to disrupted nutrient cycles and increased oxidative stress.

① Warmer water promotes N-fixation of diazotrophs, increasing N availability in coral systems.

② With abundant N, symbiotic algae quickly divide.

Under heat stress, fast-dividing algae reduce photosynthate translocation to hosts.

③ Heat increases host metabolic demands, but reduces photosynthate received by hosts.

Starved hosts switch to catabolism. Degradation of host amino acids releases more N.

④ Increased ROS release due to photo-oxidative stress.

⑤ Increased RNS release due to denitrification activities.

**Conclusion**

Efficient nutrient recycling allows corals to thrive in oligotrophic habitats, but abnormal eutrophication of nitrogen disrupts the sophisticated symbiotic relationship between coral hosts, symbiotic algae, and the microbiome. A functioning nutrient cycle is more important than the proliferation and productivity of individual species: a modest rise (1–2°C) in temperature might not kill individual organisms, but it leads to nitrogen enrichment and triggers a breakdown of the symbiotic relationship between the host and algae, which result in bleaching (Fig. 7).

Researchers have found algal symbionts that increase coral heat tolerance both in natural habitats (Berkelmans and van Oppen, 2006) and in experiment (Buerger et al., 2020). Heat-evolved Symbiodiniaceae releases less ROS and produces more photosynthates under heat stress. It would be interesting to study whether heat-evolved strains of *Symbiodinium* have different responses to nitrogen enrichment compared to their wild-type counterparts. Another interesting avenue for future study is that although fast dividing algal symbionts (due to nitrogen enrichment) reduce photosynthate translocation to coral hosts under heat stress (Rädecker et al., 2021), it is unclear whether such reduction will persist when fast symbionts division is triggered by only nitrogen enrichment (without heat stress).

The rate of coral evolution and natural selection might not be able to catch up with the rate of climate change, unless low CO2 emission plans such as RCP2.6 and RCP4.5 are implemented (Bay et al., 2017). In addition, given the large variability in thermal tolerance between coral species (Humanes et al., 2022), warming would decrease coral diversity, leading to a fragile ecosystem with less adaptability to future extreme events (Clements and Hay, 2021).

Under current climate projections, corals will live in warmer and more acidic environments. The role of coral nutrient cycling in bleaching provides a novel perspective on coral conservation. The focus on controlling nitrogen runoff corroborates with existing conservation measures to prevent algae bloom and the expansion of oxygen minimum zones, gathering momentum for an integrated effort to protect the marine ecosystem.

**Bibliography**

Anthony, K.R.N., Kline, D.I., Diaz-Pulido, G., Dove, S., and Hoegh-Guldberg, O. (2008). Ocean acidification causes bleaching and productivity loss in coral reef builders. Proc. Natl. Acad. Sci. U.S.A. *105*, 17442–17446.

Bay, R.A., Rose, N.H., Logan, C.A., and Palumbi, S.R. (2017). Genomic models predict successful coral adaptation if future ocean warming rates are reduced. Sci Adv *3*, e1701413.

Bell, P.R.F., Elmetri, I., and Lapointe, B.E. (2014). Evidence of large-scale chronic eutrophication in the Great Barrier Reef: quantification of chlorophyll a thresholds for sustaining coral reef communities. Ambio *43*, 361–376.

Béraud, E., Gevaert, F., Rottier, C., and Ferrier-Pagès, C. (2013). The response of the scleractinian coral Turbinaria reniformis to thermal stress depends on the nitrogen status of the coral holobiont. J. Exp. Biol. *216*, 2665–2674.

Berkelmans, R., and van Oppen, M.J.H. (2006). The role of zooxanthellae in the thermal tolerance of corals: a ‘nugget of hope’ for coral reefs in an era of climate change. Proceedings of the Royal Society B: Biological Sciences *273*, 2305–2312. https://doi.org/10.1098/rspb.2006.3567.

**\* Buerger, P., Alvarez-Roa, C., Coppin, C.W., Pearce, S.L., Chakravarti, L.J., Oakeshott, J.G., Edwards, O.R., and van Oppen, M.J.H. (2020). Heat-evolved microalgal symbionts increase coral bleaching tolerance. Sci Adv *6*, eaba2498.**

**\* Burkepile, D.E., Shantz, A.A., Adam, T.C., Munsterman, K.S., Speare, K.E., Ladd, M.C., Rice, M.M., Ezzat, L., McIlroy, S., Wong, J.C.Y., et al. (2020). Nitrogen Identity Drives Differential Impacts of Nutrients on Coral Bleaching and Mortality. Ecosystems *23*, 798–811.**

Burkhardt, F. (1984). Darwin’s early notes on coral reef formation. Earth Sci. Hist. *3*, 160–163.

Clements, C.S., and Hay, M.E. (2021). Biodiversity has a positive but saturating effect on imperiled coral reefs. Sci Adv *7*, eabi8592.

Davies, S.W., Ries, J.B., Marchetti, A., and Castillo, K.D. (2018). Symbiodinium Functional Diversity in the Coral Siderastrea siderea Is Influenced by Thermal Stress and Reef Environment, but Not Ocean Acidification. Front. Mar. Sci. *5*. https://doi.org/10.3389/fmars.2018.00150.

Díaz-Almeyda, E.M., Prada, C., Ohdera, A.H., Moran, H., Civitello, D.J., Iglesias-Prieto, R., Carlo, T.A., LaJeunesse, T.C., and Medina, M. (2017). Intraspecific and interspecific variation in thermotolerance and photoacclimation in Symbiodinium dinoflagellates. Proc. Biol. Sci. *284*. https://doi.org/10.1098/rspb.2017.1767.

Donovan, M.K., Adam, T.C., Shantz, A.A., Speare, K.E., Munsterman, K.S., Rice, M.M., Schmitt, R.J., Holbrook, S.J., and Burkepile, D.E. (2020). Nitrogen pollution interacts with heat stress to increase coral bleaching across the seascape. Proc. Natl. Acad. Sci. U.S.A. *117*, 5351–5357.

**\* Evans, T.G., Pespeni, M.H., Hofmann, G.E., Palumbi, S.R., and Sanford, E. (2017). Transcriptomic responses to seawater acidification among sea urchin populations inhabiting a natural pH mosaic. Mol. Ecol. *26*, 2257–2275.**

Falkowski, P.G., Dubinsky, Z., Muscatine, L., and McCloskey, L. (1993). Population Control in Symbiotic Corals. Bioscience *43*, 606–611.

Fujise, L., Yamashita, H., Suzuki, G., Sasaki, K., Liao, L.M., and Koike, K. (2014). Moderate Thermal Stress Causes Active and Immediate Expulsion of Photosynthetically Damaged Zooxanthellae (Symbiodinium) from Corals. PLoS One *9*, e114321.

de Goeij, J.M., van Oevelen, D., Vermeij, M.J.A., Osinga, R., Middelburg, J.J., de Goeij, A.F.P.M., and Admiraal, W. (2013). Surviving in a marine desert: the sponge loop retains resources within coral reefs. Science *342*, 108–110.

Goreau, T.J.F., and Hayes, R.L. (2021). Global warming triggers coral reef bleaching tipping point : This article belongs to Ambio’s 50th Anniversary Collection. Theme: Climate change impacts. Ambio *50*, 1137–1140.

Goulet, T.L., Shirur, K.P., Ramsby, B.D., and Iglesias-Prieto, R. (2017). The effects of elevated seawater temperatures on Caribbean gorgonian corals and their algal symbionts, Symbiodinium spp. PLoS One *12*, e0171032.

**\* Hawkins, T.D., and Davy, S.K. (2012). Nitric oxide production and tolerance differ among Symbiodinium types exposed to heat stress. Plant Cell Physiol. *53*, 1889–1898.**

Hughes, T.P., Anderson, K.D., Connolly, S.R., Heron, S.F., Kerry, J.T., Lough, J.M., Baird, A.H., Baum, J.K., Berumen, M.L., Bridge, T.C., et al. (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science *359*, 80–83.

Humanes, A., Lachs, L., Beauchamp, E.A., Bythell, J.C., Edwards, A.J., Golbuu, Y., Martinez, H.M., Palmowski, P., Treumann, A., van der Steeg, E., et al. (2022). Within-population variability in coral heat tolerance indicates climate adaptation potential. Proc. Biol. Sci. *289*, 20220872.

Jinkerson, R.E., Russo, J.A., Newkirk, C.R., Kirk, A.L., Chi, R.J., Martindale, M.Q., Grossman, A.R., Hatta, M., and Xiang, T. (2022). Cnidarian-Symbiodiniaceae symbiosis establishment is independent of photosynthesis. Curr. Biol. *32*, 2402-2415.e4.

Krueger, T., Hawkins, T.D., Becker, S., Pontasch, S., Dove, S., Hoegh-Guldberg, O., Leggat, W., Fisher, P.L., and Davy, S.K. (2015). Differential coral bleaching—Contrasting the activity and response of enzymatic antioxidants in symbiotic partners under thermal stress. Comp. Biochem. Physiol. A Mol. Integr. Physiol. *190*, 15–25.

Leggat, W., Seneca, F., Wasmund, K., Ukani, L., Yellowlees, D., and Ainsworth, T.D. (2011). Differential responses of the coral host and their algal symbiont to thermal stress. PLoS One *6*, e26687.

Lesser, M.P. (1997). Oxidative stress causes coral bleaching during exposure to elevated temperatures. Coral Reefs *16*, 187–192.

Li, T., Chen, X., and Lin, S. (2021). Physiological and transcriptomic responses to N-deficiency and ammonium: Nitrate shift in Fugacium kawagutii (Symbiodiniaceae). Sci. Total Environ. *753*, 141906.

Liao, H., Yang, Z., Dou, Z., Sun, F., Kou, S., Zhang, Z., Huang, X., and Bao, Z. (2019). Impact of Ocean Acidification on the Energy Metabolism and Antioxidant Responses of the Yesso Scallop (Patinopecten yessoensis). Frontiers in Physiology *9*. https://doi.org/10.3389/fphys.2018.01967.

**\* Malcolm, H., and April, H. (2012). The magnesium inhibition and arrested phagosome hypotheses: new perspectives on the evolution and ecology of Symbiodinium symbioses. Biol. Rev. Camb. Philos. Soc. *87*, 804–821.**

McGill, C.J., and Pomory, C.M. (2008). Effects of bleaching and nutrient supplementation on wet weight in the jellyfish Cassiopea xamachana (Bigelow) (Cnidaria: Scyphozoa). Mar. Freshw. Behav. Physiol. *41*, 179–189.

**\* Mohamed, A.R., Cumbo, V., Harii, S., Shinzato, C., Chan, C.X., Ragan, M.A., Bourne, D.G., Willis, B.L., Ball, E.E., Satoh, N., et al. (2016). The transcriptomic response of the coral Acropora digitifera to a competent Symbiodinium strain: the symbiosome as an arrested early phagosome. Mol. Ecol. *25*, 3127–3141.**

Mollica, N.R., Guo, W., Cohen, A.L., Huang, K.-F., Foster, G.L., Donald, H.K., and Solow, A.R. (2018). Ocean acidification affects coral growth by reducing skeletal density. Proc. Natl. Acad. Sci. U. S. A. *115*, 1754–1759.

Nielsen, D.A., Petrou, K., and Gates, R.D. (2018). Coral bleaching from a single cell perspective. ISME J. *12*, 1558–1567.

Noonan, S.H.C., and Fabricius, K.E. (2015). Ocean acidification affects productivity but not the severity of thermal bleaching in some tropical corals. ICES J. Mar. Sci. *73*, 715–726.

Norin, T., Mills, S.C., Crespel, A., Cortese, D., Killen, S.S., and Beldade, R. (2018). Anemone bleaching increases the metabolic demands of symbiont anemonefish. Proc. Biol. Sci. *285*. https://doi.org/10.1098/rspb.2018.0282.

**\* Pogoreutz, C., Rädecker, N., Cárdenas, A., Gärdes, A., Voolstra, C.R., and Wild, C. (2017). Sugar enrichment provides evidence for a role of nitrogen fixation in coral bleaching. Glob. Chang. Biol. *23*, 3838–3848.**

**\* Rädecker, N., Pogoreutz, C., Voolstra, C.R., Wiedenmann, J., and Wild, C. (2015). Nitrogen cycling in corals: the key to understanding holobiont functioning? Trends Microbiol. *23*, 490–497.**

**\* Rädecker, N., Pogoreutz, C., Gegner, H.M., Cárdenas, A., Roth, F., Bougoure, J., Guagliardo, P., Wild, C., Pernice, M., Raina, J.-B., et al. (2021). Heat stress destabilizes symbiotic nutrient cycling in corals. Proc. Natl. Acad. Sci. U.S.A. *118*. https://doi.org/10.1073/pnas.2022653118.**

Santos, H.F., Carmo, F.L., Duarte, G., Dini-Andreote, F., Castro, C.B., Rosado, A.S., van Elsas, J.D., and Peixoto, R.S. (2014). Climate change affects key nitrogen-fixing bacterial populations on coral reefs. ISME J. *8*, 2272–2279.

Smith, E.G., Vaughan, G.O., Ketchum, R.N., McParland, D., and Burt, J.A. (2017). Symbiont community stability through severe coral bleaching in a thermally extreme lagoon. Sci. Rep. *7*, 2428.

Stal, L.J. (2017). The effect of oxygen concentration and temperature on nitrogenase activity in the heterocystous cyanobacterium Fischerella sp. Sci. Rep. *7*, 5402.

Takahashi, S., Yoshioka-Nishimura, M., Nanba, D., and Badger, M.R. (2013). Thermal acclimation of the symbiotic alga Symbiodinium spp. alleviates photobleaching under heat stress. Plant Physiol. *161*, 477–485.

Tang, B.L. (2015). Thoughts on a very acidic symbiosome. Front. Microbiol. *6*, 816.

**\* Vidal-Dupiol, J., Zoccola, D., Tambutté, E., Grunau, C., Cosseau, C., Smith, K.M., Freitag, M., Dheilly, N.M., Allemand, D., and Tambutté, S. (2013). Genes Related to Ion-Transport and Energy Production Are Upregulated in Response to CO2-Driven pH Decrease in Corals: New Insights from Transcriptome Analysis. PLoS ONE *8*, e58652. https://doi.org/10.1371/journal.pone.0058652.**

Weis, V.M. (2008). Cellular mechanisms of Cnidarian bleaching: stress causes the collapse of symbiosis. J. Exp. Biol. *211*, 3059–3066.

Xiao, L., Johansson, S., Rughöft, S., Burki, F., Sandin, M.M., Tenje, M., and Behrendt, L. (2022). Photophysiological response of Symbiodiniaceae single cells to temperature stress. ISME J. *16*, 2060–2064.

Zhao, H., Yuan, M., Strokal, M., Wu, H.C., Liu, X., Murk, A., Kroeze, C., and Osinga, R. (2021). Impacts of nitrogen pollution on corals in the context of global climate change and potential strategies to conserve coral reefs. Sci. Total Environ. *774*, 145017.