How do local stressors interact with new disturbance regimes to drive spatial heterogeneity in community dynamics?

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1. Some reefs have transitioned from coral to macroalgae

Many coral reefs world-wide have transitioned from a coral-dominated state to a macroalgae-dominated state. These state shifts can alter biotic interactions, disrupt trophic structure, and impact ecosystem services such as fisheries production. MCR data from annual time series indicate that some reefs in the lagoons of Moorea that were formerly dominated by corals have recently become dominated by macroalgae (**Figs. 1** and **2**).

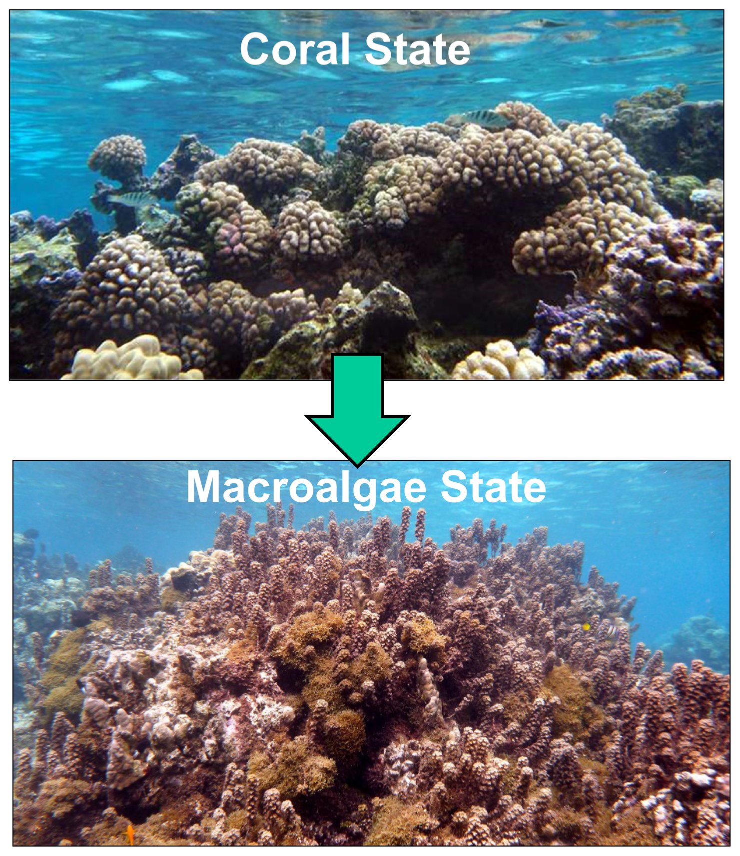
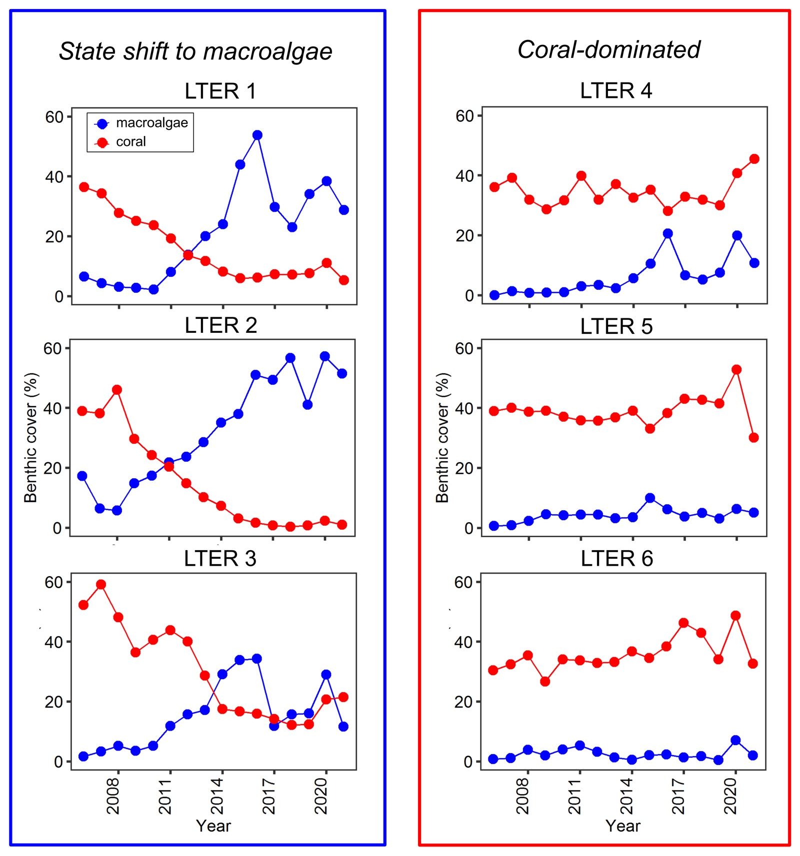


Fig. 2 Time series showing benthic dynamics at the six long-term sites on the back reef in the lagoons of Moorea. The three sites shown on the left have experienced large decreases in coral and increases in macroalgae while the three sites shown on the right have remained coral-dominated. Data from Carpenter (2022).



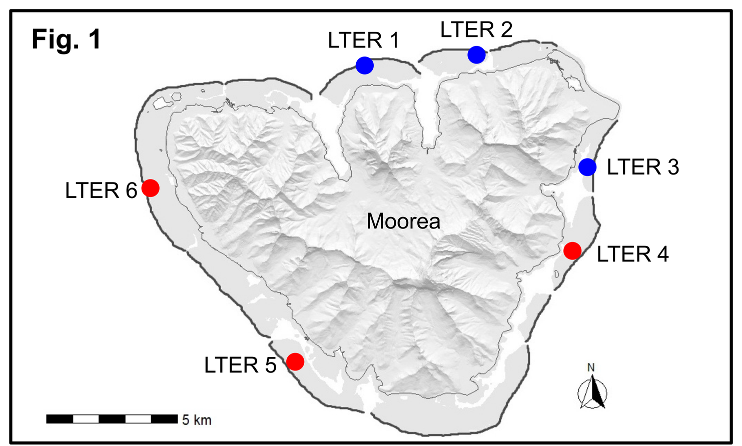


Fig. 1 Map of the island of Moorea showing the locations of the six long-term sites on the back reef in the shallow lagoons shoreward of the reef crest. Sites indicated with a blue circle have seen large declines in coral and increases in macroalgae. Sites indicated with a red circle have remained coral-dominated.

2. Algal dominance is a common reef state in the lagoons

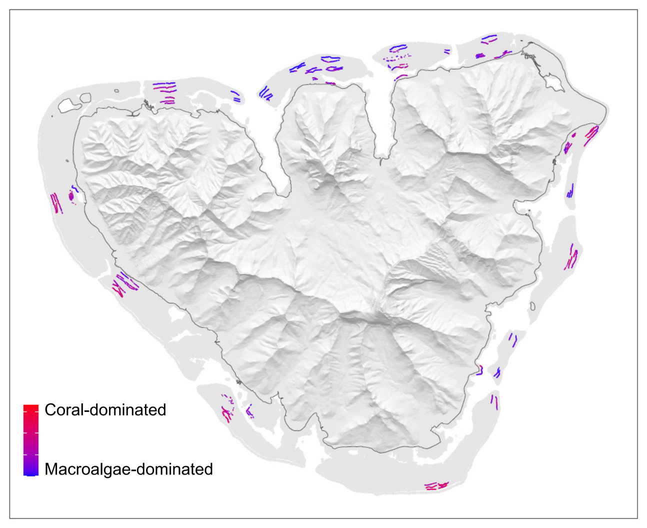


Fig. 3 Map of Moorea showing locations of 138 transects where benthic communities were assessed. Each 10 m section of a transect is color coded according to the relative abundance of coral and macroalgae.

Using machine learning, we classified benthic space holders in 230,000 images from 138 ~ 300 m long transects dispersed throughout the lagoons of Moorea (**Fig. 3**). These surveys, conducted in 2018, revealed many macroalgae-dominated reefs (**Fig. 4**). Macroalgae were especially abundant on the north shore, where recent state shifts have been observed (**Fig 3**).

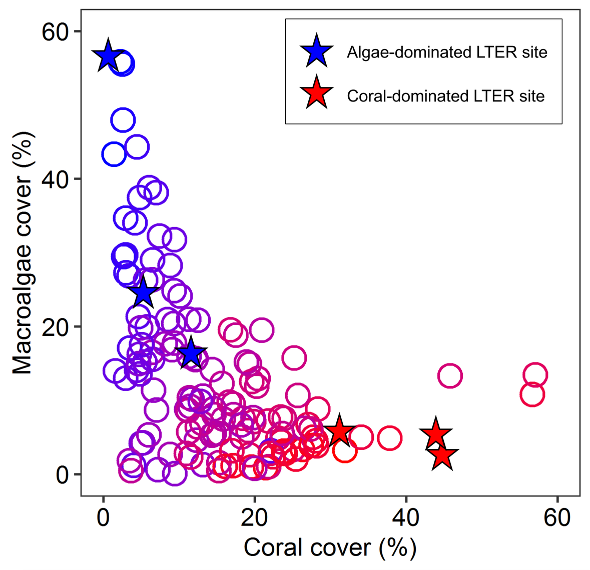


Fig. 4 Mean cover of macroalgae and coral for the 138 transects shown in Fig. 3 as well as at the 6 back reef LTER sites in 2018, when the island-wide surveys were conducted.

3. Nutrient pollution and fishing can favor macroalgae

The ocean surrounding Moorea is highly oligotrophic. Agricultural and urban run-off can elevate nutrients in the lagoons (**Fig. 5**). Excess nutrients can favor algal growth and can have detrimental impacts on reef-building corals.

Fig. 5

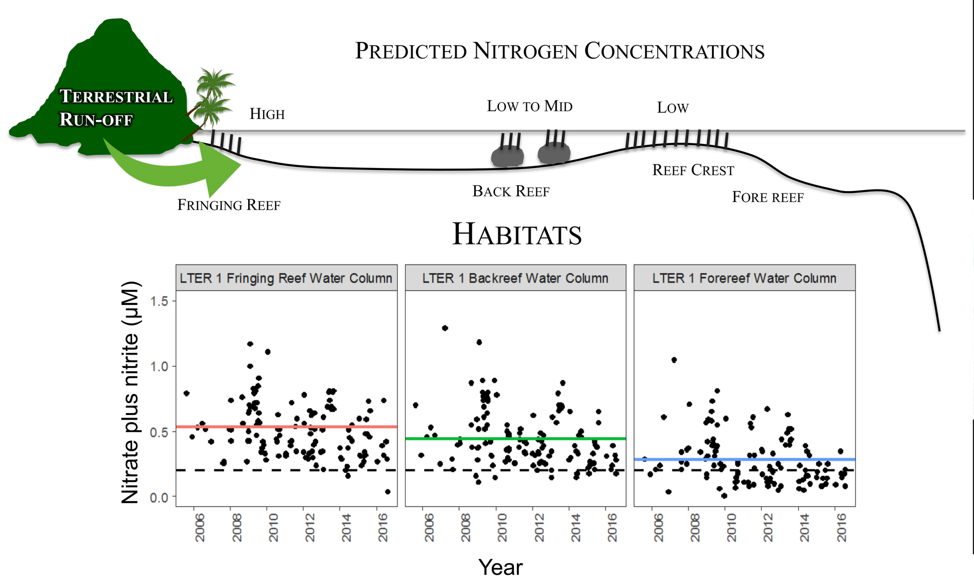
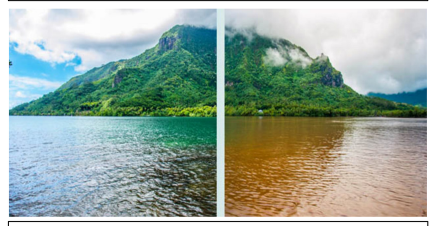


Fig. 5 Water column concentrations of nitrogen in three habitats decline with distance from shore. Solid lines indicate mean concentrations. Dashed lines show the detection limit. Data from Alldredge (2019).



Photographs of a bay on the N shore of Moorea before (left) and after (right) heavy rainfall.

Photo credit: Lauric Thiault

Fig. 6

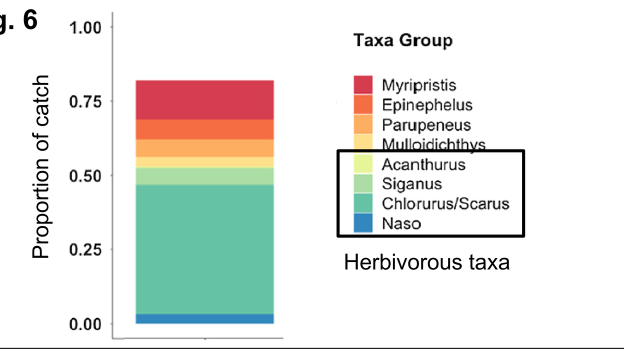


Fig. 6 Proportion of catch (by weight) sold by vendors belonging to different taxonomic groups. Note that herbivorous fishes represent > 50% of the catch. Figure adapted from Rassweiler et al. 2020.

Surveys of fishers show that herbivorous fishes are a major component of the local reef fish fishery in Moorea (**Fig. 6**). These fishes are critical for controlling the proliferation of algae that compete with corals for space on the reef.

Photo of fish being sold (note the 0.5 m sizing bar).

4. Nutrients and fishing are spatially heterogeneous

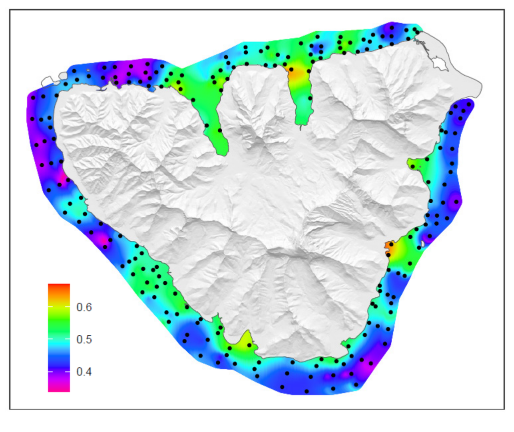
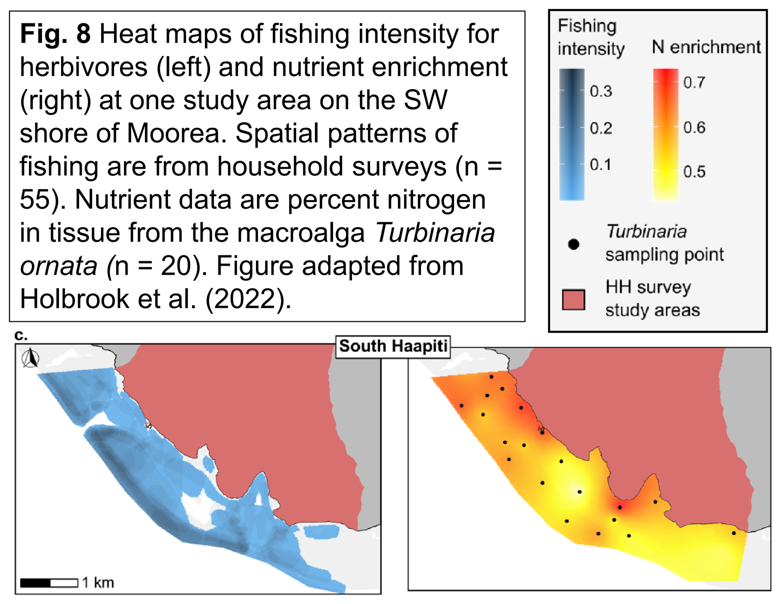


Fig. 7 Spatial patterns of nitrogen enrichment (percent nitrogen in tissue from the macroalga *Turbinaria ornata*). Figure adapted from Adam et al. (2021).

Surveys characterizing the spatial distribution of nitrogen enrichment and fishing intensity revealed both factors to be highly spatially heterogeneous and uncorrelated. Nitrogen enrichment was highest on nearshore fringing reefs and adjacent to large watersheds (**Fig. 7**). By contrast, fishing pressure was highest near reef passes and the reef crest (**Fig. 8**).

Fig. 8 Heat maps of fishing intensity for herbivores (left) and nutrient enrichment (right) at one study area on the SW shore of Moorea. Spatial patterns of fishing are from household surveys (n = 55). Nutrient data are percent nitrogen in tissue from the macroalga *Turbinaria ornata* (n = 20). Figure adapted from Holbrook et al. (2022).



5. Disturbances are spatially heterogeneous

Marine heat waves that cause coral bleaching and mortality are increasing in frequency and severity globally, including in Moorea (**Fig. 9**). Temperature dynamics can vary greatly over small spatial scales (**Fig. 10A**) leading to heterogeneous patterns of coral bleaching and mortality (**Fig. 10B**).

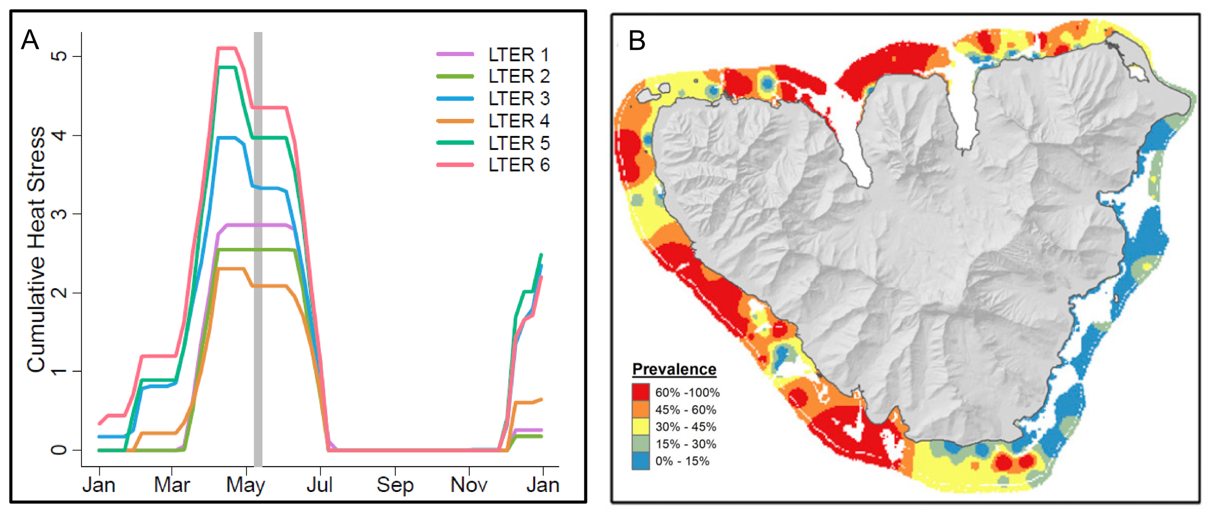


Fig. 10 **(A)** Cumulative heat stress on the fringing reef at six long-term sites during a moderate marine heat wave in May 2016 showing a large amount of variation among sites. **(B)** Distribution of coral bleaching prevalence for *Acropora* corals in the lagoons during the May 2016 heat wave showing a high degree of spatial variation. Spatial patterns of bleaching were driven in part by variation in temperature dynamics. Figure adapted from Donovan et al. (2020).

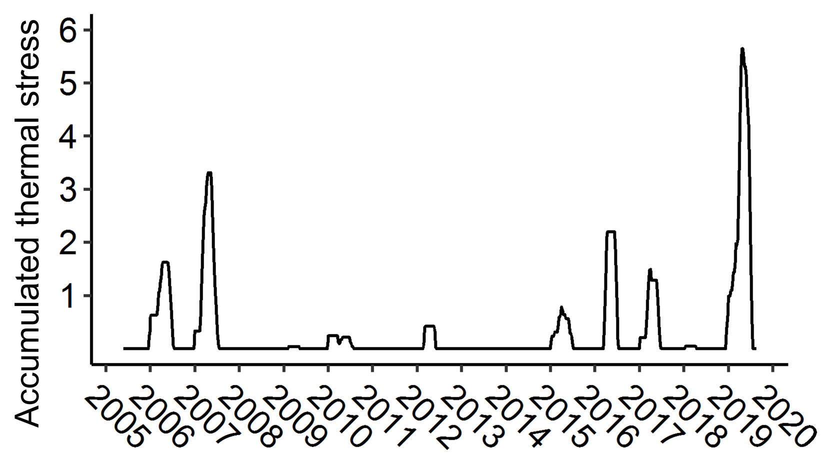


Fig. 9 History of cumulative thermal stress in the MCR time series. Note the recent increase in frequency/intensity of heat waves.

Bleached *Acropora* coral colonies in the lagoon during a marine heat wave.

6. How does spatial heterogeneity in local stressors interact with disturbance to drive benthic community dynamics?

Spatially explicit models will explore how local ecological interactions combine with disturbances caused by heat waves and chronic stressors such as fishing and nutrient pollution to drive ecological change across the seascape (**Fig 11**). Models will be parameterized with high resolution spatial data on heat wave-driven coral mortality and distributions of nutrients and fishing. Model predictions will be tested using repeated large scale surveys of benthic communities conducted by autonomous surface vehicles (ASVs; **Fig 12**).

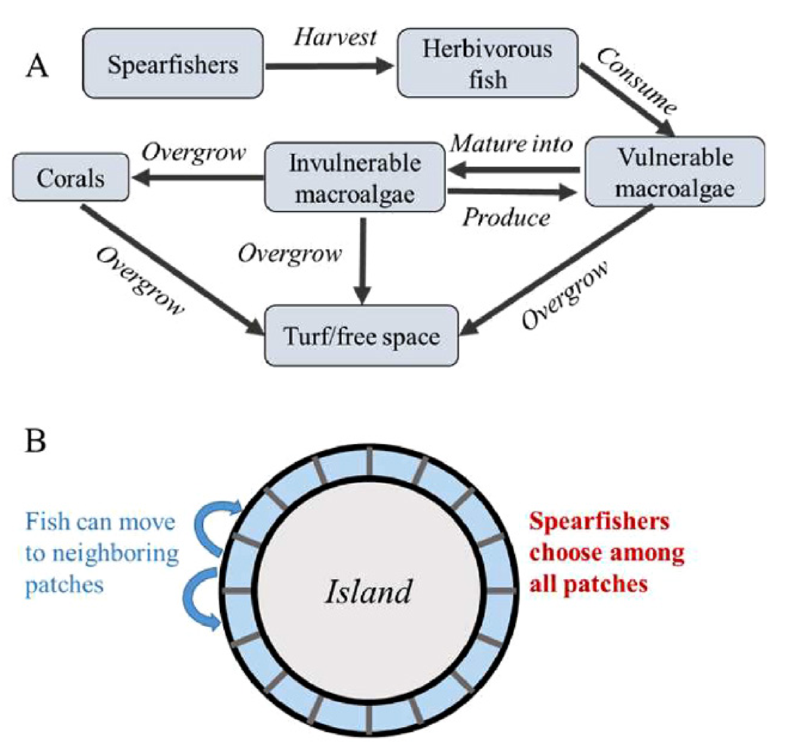


Fig. 11 Illustration of (A) interactions within a patch and (B) arrangement of patches within a spatial model of reef dynamics. Figure adapted from Rassweiler et al. (2022)

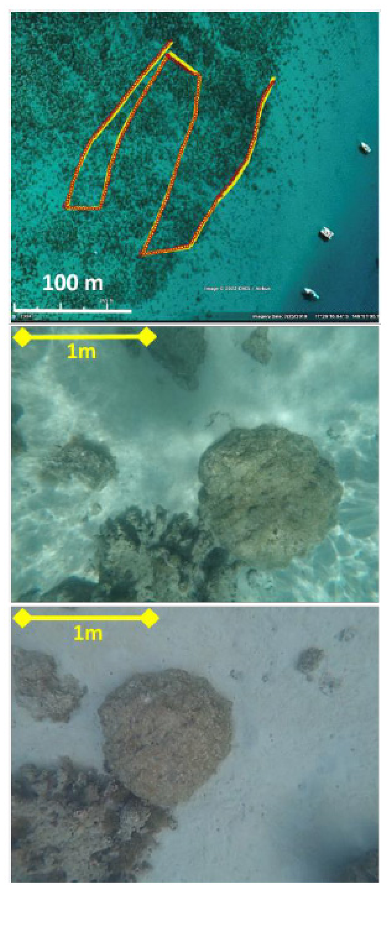


Fig. 12 Our ASV can conduct photographic surveys of lagoon habitats at 1,800 m per hour. We have programmed it to repeat prior diver-conducted surveys (**Top**). Bottom photos show images of the same coral bommie in 2020 (**Middle**) and 2021 (**Bottom**). We will conduct repeated surveys in areas influenced by different levels of disturbance and local anthropogenic stressors.

Further reading

Adam, T.C., et al. 2021. Landscape-scale patterns of nutrient enrichment in a coral reef ecosystem: implications for coral to algae phase shifts. *Ecological Applications*, 31:e2227.

Alldredge, A. of Moorea Coral Reef LTER. 2019. knb-lter-mcr.1034.9 doi:10.6073/pasta/9328a024f2bf16ecc66024f07dbcc574

Carpenter, R. of Moorea Coral Reef LTER. 2022. knb-lter-mcr.8.33 doi:10.6073/pasta/69b6927cca72a5893573276c9b0dc2a0

Donovan, M.K., et al. 2020. Nitrogen pollution interacts with heat stress to increase coral bleaching across the seascape. *Proceedings of the National Academy of Sciences*, 117:5351-5357.

Holbrook, S.J., et al. 2022. Spatial covariation in nutrient enrichment and fishing of herbivores in an oceanic coral reef ecosystem. *Ecological Applications*, 32:e2515.

Rassweiler, A., et al. 2022. How do fisher responses to macroalgal overgrowth influence the resilience of coral reefs? *Limnology and Oceanography*, 67:S365-S377.

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