**Abstract**

A quarter century after the 1998 El Niño, it is still difficult to predict how individual reefs will respond to recurring disturbances. Reports differ on the relative importance of anthropogenic influences, local geography and bleaching recurrence in determining resistance and recovery. It is assumed that coral traits largely determine winners and losers, based on bleaching susceptibility, recruitment, survival and growth. Whether this translates to the long-term fates of corals on reefs is still debated. We tracked multi-decadal coral compositional changes in reefs across the densely populated Lakshadweep Archipelago to explore how global bleaching events and local geographical factors (depth and wave exposure) influenced responses to repeated mass bleaching. Coral resistance increased with recurrent bleaching, uninfluenced by local geography. However, wave exposure regimes positively influenced recovery rates, given sufficient time between mortality events (>7 years). The overall trajectory though, was of protracted decline interspersed with periods of halting recovery, with many losers, and few resistant genera that lose less. Based on these responses, we identified six community clusters that describe contrasting long-term responses to local and global factors. Interestingly, genera with different functional traits cluster together, sharing similar fates, as a result of complex interactions between bleaching susceptibility, local geography and inter-bleaching intervals. These clusters provide a clear site-specific predictive framework of long-term community change, indicating that geography, community and time largely determine local responses to climate disturbances.

**Keywords:** Coral atolls, Lakshadweep Archipelago, El Niño Southern Oscillation, Coral bleaching, Reef resilience, Wave exposure.

**Introduction**

Over the last quarter century, the fingerprint of global climate change is increasingly evident in even the most distant reefs, once immune from anthropogenic influence (Barkley et al., 2018). With growingly intense and increasingly frequent El Niño Southern Oscillation (ENSO) events the recurrence of coral mass mortalities gives reefs little opportunity to recover (Hughes et al 2018; Sully et al., 2019). Pantropically, coral cover has reduced an estimated 14% since the 1998 ENSO (Hughes et al., 2017; Hoegh-Guldberg et al., 2018). Against this general pattern of decline however, there is a large variability in reef responses. Regions like the Great Barrier Reef are particularly susceptible, bleaching every few years, and over vast scales (Ortiz et al., 2018; Stuart-Smith et al., 2018). Other locations do better – either escaping major mass bleaching events entirely, or recovering remarkably after coral mass mortalities (Gintert et al., 2018; Sully & van Woesik, 2020). This variability occurs at regional scales as well; reefs only kilometres apart could show vastly different responses to global disturbances (Donner & Carilli, 2019; Hédouin et al., 2020; Ortiz et al., 2018). This presents a challenge for local management, making it is difficult to conceive of meaningful resilience planning given the seemingly arbitrary fates of individual reefs. Unpacking the complex interactions between local and global factors driving variations in reef response has been a major focus of research over the last 25 years (Anthony et al., 2009; Fordyce et al., 2019; McClanahan et al., 2020; McClanahan et al., 2019).

Several environmental and biotic drivers, acting at different spatial and temporal scales, together influence the relative resistance and recovery of reefs exposed to thermal stress. Ocean-wide ENSO currents interact with regional climatic phenomena such as the Indian Ocean Dipole (IOD) and local conditions (upwellings, tidal patterns, cloud cover, etc) to determine the thermal conditions corals at reefs experience ( Lesser et al., 1990; Nakamura & van Woesik, 2001; Page et al., 2019; Le et al., 2020; Xiao et al., 2020) . How corals respond to this stress varies considerably. The coral holobiont has greater adaptive capacity than first imagined, and thermal tolerance varies with zooxanthellae composition, with some coral capable of shuffling this composition in response to environmental cues (Fabricius et al., 2004; Jones et al., 2008; Guest et al 2012; Ainsworth et al 2016). Resistance then can vary between individuals, populations, communities and locations, as species coping strategies interact with global and local conditions. Large scale thermal disturbances therefore leave behind a messy patchwork of mortality, with reefs radically altered in benthic composition, architectural complexity and ecological functions.

Generalising about recovery is an even harder problem than resistance. Population recovery typically takes decades, placing it outside the scope of short-term laboratory and field-based investigations. We have had less than three decades since the first global mass mortality (in 1998) to document long-term benthic trends and unpack generalisable mechanisms of recovery. The picture emerging from global case studies is far from clarifying, with some reefs recovering smartly, while others recover more slowly, or remain dominated with low-profile algae (Tebbett et al., 2023). Why some reefs recover so well, while others decline or remain in a state of arrested recovery is difficult to predict.  Supply-side and post-recruitment processes clearly influence paths to recovery, but we do not yet have a good enough measure of these basic rates for most tropical reefs. Fish, herbivores in particular, may confer resilience post-disturbance, and land-based nutrients may impede recovery by promoting algal growth in some coastal reefs (Roff & Mumby, 2012). Perhaps more critically, recovery can differ with local environmental conditions and geography, with studies highlighting nutrients, temperatures, turbidity, local bathymetry and other physical drivers, such as wave exposure, in determining recovery trajectories (Lange et al., 2021). Local hydrodynamics appears to be critical, and can serve as a strong environmental filter of recovery trajectories. For instance, windward slopes often show faster rates of coral regrowth, linked to the availability of stable settlement substrate after mass mortalities (Yadav et al 2015). Above all, time is a powerful factor in recovery – given enough time between disturbances many reefs show handsome recoveries, though not all (Gouezo et al., 2019; Robinson et al., 2019).

Both reef resistance and recovery then are influenced by global as well as local factors to various degrees. Why is this important?  One unsettled question is how effective local management can be in the light of global change. Do spatial planning exercises of the likes of MPAs or fisheries reserves make any difference in mediating reef recovery trajectories? Or are reefs merely at the mercy of larger, global-scale processes where the intensity of bleaching, and inter-bleaching intervals are all that determine reef conditions? In answering these questions, most long-term studies unsurprisingly track rates of live coral cover as a simple measure of reef resistance and recovery (Brown et al., 2019; Fine et al., 2019). As the principal biogenic agent on reefs, live coral cover stands in as a good index of the functional health of the reef. However, live coral can often mask dynamic rearrangements of coral assemblages in space and time. Differences in coral life history strategies could strongly mediate their susceptibility to thermal stress and rates of recovery post-disturbance (Darling et al., 2012). The rapid recovery recorded in resilient reefs could merely reflect the regrowth of fast-growing ‘competitive’ and ‘weedy’ branching species of *Acropora* and a few others.  Yet, while fast-growing species are disproportionately important, they do not represent the entire range of architectural, wave-attenuating, and accretion and sediment generating functions that habitat-forming corals provide. For instance, while some species may not drive trends in coral cover, they may be important structural species contributing to reef stability, and better adapted to bleaching (Alvarez-Filip et al., 2011; Darling et al., 2017). Reefs dominated by these communities could signify very different reef behaviours with distinct functional contributions. Changes in live coral, valuable as they are, simplify what are in reality multiple paths to recovery, each with different implications for reef responses to climate change. While coral traits help provide an expectation for how coral communities may fare, it is still unclear how well they predict the long-term fates of corals on reefs.

We document compositional changes in coral communities over 24 years in 12 reefs of three atolls in the Lakshadweep Archipelago (Indian Ocean), exploring the influence of global climate change and local environmental drivers in determining paths of reef resistance and recovery after major ENSO-linked disturbances. Lakshadweep has been exposed to several large ENSO events and has suffered significant coral mass mortalities since over the last quarter century (in 1998, 2010 and 2016; Yadav et al., 2018). We describe how patterns of resistance and recovery have changed with each recurrent bleaching event and inter-bleaching interval, and how depth and exposure mediate these trends. We document compositional shifts underlying these trajectories and identifying clear site-specific community-level responses to global bleaching and local geography. We discuss the functional implications of this changing composition for reefs in the age of climate change.

**Methods**

*Study Area and design*

The Lakshadweep Archipelago is a group of 12 coral atolls in the northern Indian Ocean, ten of which have populated islands. With a density of more than 2,000 ind/km2, Lakshadweep is among the most densely populated atoll systems in the world, and the reefs have witnessed a recent expansion of commercial fishing for mainland markets (Jaini et al., 2018).

The archipelago experienced 3 increasingly intense ENSO events in 1998, 2010, and 2016 (Yadav et al., 2018). Long-term monitoring sites were established in 1998, right before the 1st coral mass mortality. We monitored three atolls, Agatti, Kadmat, and Kavaratti, sampling two sites per atoll and two depth zones per site. Sites were chosen to represent strong exposure gradients due to the south-west monsoon with locations on east-facing (sheltered) and west-facing (exposed) aspects (See Fig. 1). We used a GIS-based modelling approach, following the procedure by Ekebom et al (2003), to determine fetch distances (See Supplementary material, methods 1.). We then modelled critical wave parameters such as significant wave height, and wave period, using wind data gathered from MeteoBlue (2022) and arrived at wave energy flux around three atolls using appropriate fetch or duration-limited equation (Resio et al., 2003).

*Benthic transects*

We sampled each site at 2 depth classes - deep (~16m) and shallow (~8m). Data on benthic composition was gathered in 1x1 m quadrats, placed at a 10 m interval on three randomly located 50 m transects at each depth (n~18 quadrats per depth class per site). Data was recorded either directly *in-situ* (1998-2003) or with digital photographs (2007 onwards). Digital photoquadrats were analysed with ImageJ (Schneider et al., 2012) where the percent cover of broad benthic categories were estimated using overlaid 10x10cm grids. Live coral was further identified to the genus, based on Veron (2000) classification. Initial surveys in 1998 and 1999 did not record genus-level information. We tracked changes in coral composition from 1998 to 2022, with some breaks (See supplementary material for details). We present data for 13 years across this 24-year period.

*Bleaching resistance and post-bleaching recovery*

We first estimated the mean coral cover at each site and depth class. Across the dataset, we calculated a measure of ‘Resistance’, defined as the coral cover immediately after a bleaching event subtracted from the last available cover before the event. Higher negative values indicate a sharper decline in cover, whereas positive values show an increase in cover after a bleaching event. We also estimated a ‘Recovery rate’, defined as the change in cover between the 1st year after a bleaching event, and the last available year before the next event, divided by the number of years between events. Lower values indicate little increase in coral cover. For recovery we divided the dataset into three phases, corresponding to the time period between multiple bleaching events: Phase 1: 1999-2007, post the 1998 event and before the 2010 event; Phase 2: 2011-2015, post the 2010 event and just before the 2016 event, and Phase 3: 2017-2022, post the 2016 event up to 2022 (see Table 1 in supplementary material for summary of variables). We used linear regression models to identify how exposure interacted with bleaching events and shaped reef recovery and resistance trajectory. Both recovery and resistance data, which are derived indices, met the assumptions of normality and homoscedasticity based on visual inspections of residuals and fitted values. In both cases, the explanatory variables used in the model were i. the bleaching phase (1, 2 or 3) and ii. site exposure (kW.m-1). All analysis was done using R version 4.2.1.

*Post-bleaching changes in coral assemblages*

We modelled temporal changes in benthic cover of 22 of the most abundant (from our dataset) coral genera. Since our benthic data were non-normal and percentage based, with a strong right skew, we used a weighted logistic distribution. The weights corresponded to the number of grids within a quadrat which were sampled, in this case 100. We therefore used a generalised mixed effects model with a logistic error distribution to model trends in total coral cover and individual coral genera over time per quadrat. The fixed explanatory variables used in the model were i. the years since a mass bleaching event (inter-bleaching interval), ii. the bleaching phase (1, 2 or 3), iii. depth class (deep or shallow) and iv. site exposure (kW.m-1). The atolls (Agatti, Kadmat, and, Kavaratti) were introduced as random variables. The coral genera value for each quadrat was used as a datapoint in the analysis. We then used bootstrapped confidence intervals to extrapolate the estimate and the errors around them to the population surveyed. All analyses were done using R version 4.2.1 using the package ‘*lme4*’.

*Classifying coral assemblages*

To further synthesize the results of the regression models, we used hierarchical cluster analysis to group coral genera with similar responses, based on the fixed effects used in the GLMM. Using the slope and standard error for each variable in the regression, we generated 10,000 Montecarlo simulated slopes for each coral. We then used Ward’s D2 method for an agglomerative algorithm to classify corals into distinct clusters (Darling et al., 2012) based on their long-term responses, and repeated this step for all 10,000 iterations. We identified six distinct clusters of coral genera based on their similarity of response. We then computed the individual probability of each genus being classified with each of the six clusters and used a 40% probability cut-off to determine the final coral clusters. We then identified the number of simulations (of 10,000 iterations) that matched this clustering pattern. The entire range of values for each of our variables was then plotted as a probability density function to describe ‘behaviours’ of each cluster.

**Results**

*Exposure variation across the islands*

*\*ADD FIGURE 1 HERE\**

*Figure 1. Left: Map of Lakshadweep Archipelago with the studied atolls (Kadmat, Agatti and Kavaratti) marked in bold. Right: Annual wave exposure model showing a clear contrast between eastern (sheltered) and western (exposed) aspects of the 3 studied atolls. Exposure is measured in kW/m of wave crest. The triangles mark the location of long-term monitoring sites.*

Exposure varied considerably around each atoll, strongly influenced by the annual summer-monsoon (Fig. 1).  The north-south orientation of most atolls in relation to the dominant winds of the southwest monsoon created strong contrasts between leeward, east-facing and windward, west-facing reefs. The difference in wave power arriving at the reef crest on western reefs was orders of magnitude higher than waves arriving at the eastern crest. The post-monsoon season showed a slight reversal in exposure patterns but the difference in magnitude was not as stark as the monsoon season (See Fig. 1).

*Trends in live coral cover through time: Resistance and recovery*

\*ADD FIGURE 2 HERE\*

***Figure 2.*** *Change in mean percent coral cover at deep and shallow sites at Kadmat, Agatti and Kavaratti. Vertical downward arrows mark the three mass bleaching events that affected Lakshadweep reefs (1998, 2010, 2016). Horizontal dashed lines indicate the average coral cover for that site over the past 24 years. Error bars are 95% Confidence Intervals of estimated mean coral cover.*

Lakshadweep reefs have experienced three coral mass mortalities since the late 1990s: in 1998, 2010 and 2016. There was considerable variation in reef responses to these disturbance events between atolls, aspects and depths (Fig. 2). After the 1st bleaching event, western sites across all 3 atolls recovered well by around 2007, before the 2nd bleaching event in 2010 (Fig. 2 and Fig. 3). The bleaching phase itself was an important predictor of recovery with the 1st and (to a lesser extent) the 3rd phase showing higher recovery rates compared to recovery in the second phase (Fig. 3; see Supplementary Fig. 1 & Table S2).

*\*ADD FIGURE 3 HERE\**

***Figure 3:*** *Biplot of resistance and recovery indices indicating how individual sites fared in each bleaching phase. Overall resistance increased with each bleaching phase, with all sites tending towards 0. recovery rates were highest in Phase 1, noticeably lowers in Phase 2, and shows an increase in Phase 3.*

The recovery trajectory however, was not entirely linear, with a steeper growth after 5-6 disturbance-free years (Supplementary Fig. 2). There was also a broad separation between more sheltered eastern sites and exposed western sites, which showed considerably higher rates of recovery. Linear models showed an interacting effect of wave exposure and phase with recovery rates most pronounced for the 1st bleaching phase event, while the 2nd and 3rd phases, showed marginal, statistically insignificant increases in this trend (Supplementary Table S2). The one exception is Kadmat, which in the 3rd phase, showed higher recovery on its sheltered site (Fig. 2; Fig. 3). In contrast with recovery rates, the overall resistance increased with bleaching phase and did not show any discernible effect of wave exposure except for the 2nd bleaching event. Additionally, the intercepts of all three bleaching phases showed a statistically discernible difference (Fig 3; see supplementary Fig. 1). With each phase, our monitored sites converged towards zero along the resistance axis, indicating an increase in overall resistance – and in some instances, an increase in coral cover post-bleaching. This, despite heat stress (degree heating weeks) increasing with each event (Yadav et al., 2018).

*Changes in coral genera composition: GLMM results*

*\*ADD FIGURE 4 HERE\**

**Figure 4.** Results of the GLMM highlights a varied response to the effects of recovery time, bleaching event, depth category, and exposure regime on 22 genera of corals along with the total coral cover in the 1st row. Positive values indicate an increase in the coral cover of a genus, while negative values indicate a decline in cover. Positive values of shallow indicate their abundance in shallower sites and vice versa.

The shifting composition of coral genera across time contributed to trends in resistance and recovery. At the end of each recovery period, there were clear shifts in the composition of dominant corals (Supplementary Fig. 3). Recovering reefs in the 1st phase had a relatively large proportion of *Acropora* in shallow sites, while slow-growing *Faviids* and other corals contributed significantly to deeper sites (Supplementary Fig. 3). In the considerably shorter, 2nd recovery phase, *Pocillopora* increased along together a reduction in *Acropora*; *Porites*, especially at deeper sites. At the end of the 3rd recovery (phase 3) we observed a potential return to the compositional patterns of the 1st phase, with *Acropora* re-establishing itself in the community, while a mix of ‘*other*’ corals gaining in cover as well.

Mixed effects models showed the varied fates of coral genera over the last quarter century. None of the models showed any discernible influence of random effects. Genera were all differentially influenced by inter-bleaching interval (time since the last disturbance), the bleaching phase, depth and exposure, however a majority of coral genera showed a decrease with successive bleaching events (Fig. 4, see Table 4 in supplementary material). *Acropora* was strongly associated with shallow sites; was positively correlated with wave exposure; increased with inter-bleaching interval, even though its cover reduced discernibly with every successive bleaching event. In contrast, the cover of *Pocillopora* increased with every bleaching phase, and was found in both shallow and deep sites, but was preferentially found in sheltered sites. Corals such as *Porites* tended to be found more deeper, more exposed locations. Almost all other genera such as *Acanthastrea*, *Psammocora*, *Montastrea* and *Galaxea* declined significantly with bleaching phase. While corals such as *Pavona* and *Symphyllia*, grew preferentially at sheltered locations, most common genera favoured exposed reefs.

*Classifying coral assemblages*

*\*ADD FIGURE 5 HERE\**

**Figure 5.** Results of the GLMM estimates, over 10,000 iterations were used as input variables to cluster corals based on their similarity of response (panel a). ‘Recovery’, ‘Phase’, ‘Depth’, and ‘Exposure’ correspond to the variables of interest. A total of 340 simulations out of 10,000 yielded this exact clustering and thus the probability density graph to the right shows the distribution of GLMM estimates for all 340 simulations. The density graphs (panel b) highlight the confidence with which we can ascribe behaviour to each cluster. The x-axis represents the effect sized from our GLMM slopes for each genus, while the y-axis highlights the distribution of all 340 data points with particular emphasis on the spread of the data.

The results of the Montecarlo simulations show individual probabilities of corals that can be classified under each cluster (Fig. 5 and Supplementary Table 5). Further, the hierarchical cluster analysis and Montecarlo simulations identified 6 broad clusters, grouping genera that show similar responses in relation to depth, exposure, inter-bleaching interval and bleaching phase (Fig. 5). Thus, for instance, cluster 1 includes corals that recover relatively well, are found at all depths; tend to be more abundant at more exposed regions; but show a marked decline with successive bleaching events. Cluster 5 corals in contrast are found disproportionately on exposed shallow locations, are highly susceptible to bleaching, but recover the fastest after each event. Cluster 4, with a large number of genera are similar to cluster 1 but show a discernibly stronger decrease after bleaching events, and have some of the slowest recovering corals. Across the board, most genera (with the exception of Cluster 2 and 6 corals) have declined with repeated bleaching events.

**Discussion**

Over the last few decades, time and successive bleaching events have principally shaped recovery of coral reefs in Lakshadweep. With every subsequent ENSO event, Lakshadweep’s coral assemblages show a trend of increasing resistance, largely driven by shifts in coral composition. As the frequency of ENSO events increases (Hughes et al., 2018), reefs surrender their marginal gains every few years with the next heat wave, remaining in low coral states.  Given enough time though, reefs do show some recovery, even if it is patchy and uneven between sites, exposures and depths. Through this patchiness however, patterns emerge of mixed community responses, broadly based on bleaching susceptibility and strong geographical filtering.

At first glance, the long-term patterns of resistance we documented suggest that Lakshadweep reefs are increasingly impervious to temperature anomalies as either their composition shifts towards tolerant genera (Darling et al., 2012), or thermal experience confers increasing assemblage-wide bleaching resistance (Guest et al., 2012). Lakshadweep reefs have shifted in dominance towards more resistant genera, predominantly *Porites*, but including *Goniastrea*, *Favia*, *Pocillopora*, *Goniopora*, and *Montipora*. Their relative abundance was high after each bleaching event, as more susceptible genera declined. Despite this apparent resistance however, most genera have reduced overall (Fig. 5 & 6), indicating an assemblage gradually ratcheting downward. The overall trend is of a protracted decadal decline, interspersed with periods of halting recovery. While there is a lot of emphasis on the shifting fates of corals on reefs (Hughes et al., 2017), our results identify few winners over the long term, just some genera that lose less. The emerging assemblage comprises species with either significantly slower growth rates than earlier reef dominants, restricted largely to deeper depths, or with low natural abundances. Given the increasing frequency of ENSO events, these remnant assemblages are unlikely to contribute much to overall reef recovery, and their contribution to critical reef functions such as accretion, sediment production and wave attenuation is likely to be small. At best, they may help maintain reefs in states of arrested recovery until faster growing genera regrow.

\*ADD FIGURE 6 HERE

**Figure 6.** A conceptual diagram summarising the results of long-term coral fates in the Lakshadweep. Contrasting exposure regimes due to south-west monsoons and depth of the reef, are two local geographic filters that have been used in the analysis. Placement of the clusters along the atoll margins signify any form of geographical filtering. Curves under each cluster highlights their characteristic recovery and post-bleaching behaviour.

*Recovery patterns and composition*

While resistance patterns are uninfluenced by local factors, the patchiness in reef recovery is linked, at least in part, to physical exposure, with recovery rates increasing across the exposure gradient. The strength of this trend varies with inter-bleaching intervals, and manifests only when the reef has had sufficient time to recover. It was strongest in the first (and longest) post-bleaching phase, disappears almost completely in the second (and shortest) post-bleaching phase, and reappears weakly post-2016, in the third post-bleaching phase. The availability of stable substrate for recruitment and growth may be essential for long-term recovery; the strong annual monsoons and episodic storms, mediates this stability by sweeping dead, unstable coral substrate from shallow windward slopes (Yadav et al., 2016).  Compositionally, these recovery patterns are dominated by the dynamics of a few key genera: fast growing species of *Acropora*, a few *Pocillopora* species, *Porites*, a resistant, relatively unchanging constant on the reef, and other slow-growing *Faviids*, which are a patchy but constant element in post-disturbed reefs (Fig. 4). Over the last 24 years, *Acropora* and *Pocillopora* have shifted in dominance on these reefs based on their relative bleaching susceptibility and recovery potential. Given the high bleaching susceptibility of most *Acroporiids*, they tend to decline dramatically with every thermal anomaly, but also recover given at least 6-7 years without disturbance. The genus *Pocillopora*, predominantly *P. verrucosa* with interspersed *P. meandrina*, and *P. eydouxi* is relatively more bleaching tolerant than *Acropora*, and since 1998, is one of few genera to have benefited from periodic declines of *Acropora*, often replacing it as the dominant branching form, at least in the initial post-bleaching years (supplementary Fig. 3). *Pocillopora* has however, itself been subject to significant mortality, linked both to occasional bleaching as well as storm damage (Riyas et al., 2020). Given time, *Acropora* re-establishes, at least on shallow exposed reefs, replacing *Pocillopora* as a dominant. As a result, the shift from *Acropora* to *Pocillopora* is highly dynamic through time.

The trends described by these dominant genera mask subtler compositional patterns that may also be geographically filtered. The clusters we identified from the GLMM results and Montecarlo simulations group coral genera based on shared long-term fates (Fig. 5 & 6). Several generalised responses emerge that describe distinct community-level behaviours in relation to bleaching responses and local geography. Most clusters show at least some degree of geographical filtering in relation to depth and exposure. The only cluster that is spatially ubiquitous is cluster 2, with its genera (*Pocillopora* and *Favia*) found across depths and exposure. All the rest separated with exposure, depth or both. Thus clusters 5 and 6 were most characteristic of shallow locations on exposed and sheltered aspects respectively, whereas cluster 3 was most abundant in deeper locations, independent of exposure. Clusters 1 and 4 were found mostly on exposed fronts, but at both depths. Each cluster also described major differences in their long term trends, based on bleaching susceptibility and post-bleaching recovery. Cluster 1 and 4 show differences in their magnitude of decline with successive ENSO events and post-bleaching recovery, even though their distributions seem to be similar. Cluster 4 are a mix of genera that show a strong decline with successive ENSO events, similar to cluster 5 (composed of *Acropora* and *Hydnophora*), but differ largely in their rates of recovery post-bleaching. Interestingly, most clusters are a mix of stress-tolerant, weedy and intermediate genera (*sensu* Darling et al., 2012), hinting that simple life history classifications may not completely predict species survival in the face of climate change. This apparent disconnect between life history and long-term trends shows that corals with varied traits could share similar fates in relation to repeated disturbance, due to a complex interaction between bleaching susceptibility, recovery capacity and local geographical factors like exposure and depth. Although these groupings are necessarily tentative, as a broad predictive heuristic, this approach is useful in mapping the relative vulnerabilities of individual reefs across similar systems, and help clarify the matrix of dynamic communities that emerge in post-disturbed reefs. Overall, this community analysis paints a picture of an ecosystem in constant flux, composed of multiple assemblages that respond differentially to the same set of global disturbances.

*Compositional shifts and their functional consequences*

The complexity of compositional rearrangements through time makes it self-evident that the recovery of live coral does not represent a compositional recovery. The recovering reef is compositionally quite distinct from past reefs, with a subtly changed suite of functions. The recovering reef is initially dominated by slow-growing massives and encrusting forms, and while fast-growing branching and tabular forms do eventually make a comeback, they remain small and scattered, often at locations with certain geophysical conditions. This simplified architecture signifies a major change in reef architecture, particularly for habitat associates and structure-dependent species (Kerry & Bellwood, 2015; Karkarey et al., 2014, 2017)). Coral compositional changes also strongly influence rates of carbonate production and reef accretion (Perry et al., 2018; Patel et al., 2023). For highly populated, low-lying atolls like Lakshadweep, a loss of accretion potential could, in the medium term, present a serious habitability challenge for island communities (Duvat et al., 2021). More broadly, for reef-dependent island societies, the functions of a changing reef composition mean much more than live coral cover, and the reduced provisioning and regulatory services these functions imply directly impact the livelihood, wellbeing and survival of climate-vulnerable societies like Lakshadweep.

*Managing for resilience*

What do the decadal patterns of mixed resistance and recovery in Lakshadweep say about our ability to manage tropical reefs for climate resilience? The difficulty of confronting the climate crisis is that its causes are global and its impacts diffuse, making our traditional conservation toolbox, designed for more spatially-explicit biodiversity crisis, rather ineffective. In attempting to repurpose traditional ecosystem management for the post climate change age, researchers have struggled to show that areas kept pristine from human influence are more climate resilient (Bates et al., 2019; Mellin et al., 2016). Yet, given the scale and character of climate disturbances, it is difficult to conceive how conventional forms of local management could protect coral reefs from ocean-wide disruptions in sea surface temperature. Protection or remoteness do not, on their own, confer resistance to reefs, nor are they a prerequisite for recovery. We need to think beyond our biodiversity management toolbox and find more realistic solutions for a post climate change age. We have to first accept that we are largely at the mercy of local geography and the return time of global disturbances when it comes to reef resistance. Local factors, altered community assembly and time make all the difference in determining reef responses to climate disturbance. There is no getting away from the reality of repeated ENSO events, and it is difficult to see how reefs will be able to deal with climate change in the long-term without significantly reduced diversity and compromised ecosystem function. While the apparent increasing resistance of reefs subject to repeated disturbances is comforting at first, it comes at the cost of many functionally critical groups that contribute to the complex physical architecture of a healthy reef. We can perhaps hope that these relatively resistant corals can confer some long-term background stability and make-up reefs that can survive on functional minimums (Mumby, 2017).

Recognising that local environments play a role in patchy recovery should be critical in spatial planning – potentially reducing additional impacts on post-disturbed reefs and enhancing rates of natural recovery after each disturbance event. Eventually, the global reach of the climate crisis needs us to tackle problems globally *and* locally using the instruments appropriate for each scale. We can address local impacts as best we can with careful spatial planning and reducing anthropogenic impacts that can compound the effects of mass bleaching. In the long run however, it is critical that we call the crisis by its name and recognise that the integrity of tropical reefs, like the rest of global biodiversity, cannot sustain the seemingly impervious logic of the global economic order (Morrison et al., 2022). Without radical policies, laws and actions to address these ultimate causes, anything we do locally for reefs will be symptomatic and palliative fixes.

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