

# Thermal Bleaching Events, Species-Specific Recovery Trajectories, and Reef Biodiversity Loss in the Lakshadweep Archipelago and Andaman Reefs

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## Abstract

*India's tropical coral reef ecosystems — centred on the Lakshadweep Islands in the Arabian Sea, the Andaman and Nicobar Islands in the Bay of Bengal, and the Gulf of Mannar fringing reefs along the Tamil Nadu coast — support exceptional marine biodiversity and provide critical ecosystem services to coastal and island communities including fisheries, coastal protection, and tourism valued at over INR 18,000 crore annually. Accelerating sea surface temperature rise in the Indian Ocean, amplified by the Indian Ocean Dipole and periodic El Niño-Southern Oscillation events, has transformed mass coral bleaching from a rare disturbance into a recurring annual threat, with the 2019 and 2022 bleaching events representing the two most severe thermal stress episodes recorded in the Indian reef monitoring period.*

*This study presents a five-year longitudinal analysis (2019-2024) of bleaching severity, species-specific recovery trajectories, and cumulative biodiversity indicators across eighteen permanent reef monitoring stations across the Lakshadweep and Andaman reef systems. Sea surface temperature anomalies from NOAA Coral Reef Watch satellite data were linked to in-situ bleaching severity assessments conducted by trained reef surveyors. Results demonstrate that bleaching severity in 2022 exceeded 2019 levels at all stations, with branching *Acropora* and *Montipora* species showing the lowest recovery indices (0.19-0.34). Overall coral cover declined from 38.4 percent in 2019 to 24.7 percent in 2024, a 35.7 percent reduction. Shannon diversity index declined significantly, driven by disproportionate loss of thermally sensitive branching coral morphologies.*

**Keywords:** coral bleaching, Lakshadweep, Andaman reefs, sea surface temperature, reef biodiversity, *Acropora*, recovery index, Indian Ocean, NOAA CRW, marine ecology

## 1. Introduction

India's coral reef ecosystems represent a uniquely valuable component of the nation's natural capital, distributed across three distinct biogeographic zones that together support over 500 coral species and thousands of associated reef fish, invertebrate, and algal species. The Lakshadweep Islands — India's only atolls — sustain reef systems with coral cover values historically exceeding 60 percent at pristine sites, providing the primary defence of island communities against wave erosion and storm surge in an archipelago where land elevation rarely exceeds 2 metres above sea level. The Andaman and Nicobar Islands host the most species-diverse Indian reef systems, with their position at the edge of the Coral Triangle biogeographic zone generating biodiversity levels rivalling Southeast Asian reefs. The Gulf of Mannar fringing reefs support the livelihoods of over 100,000 traditional fisher households across the Tamil Nadu coast.

Mass coral bleaching events, driven by sea surface temperature anomalies exceeding the thermal tolerance thresholds of coral-zooxanthellae symbioses, have increased dramatically in frequency and severity across the Indian Ocean over the past two decades. The 1998 bleaching event — associated with the exceptionally strong El Niño of that year — caused catastrophic coral mortality across the Lakshadweep atolls, with some stations losing over 80 percent of coral cover. The recovery period of approximately fifteen years before the next major bleaching event (2010) allowed partial restoration of coral communities, but the compression of bleaching recurrence intervals to two-to-three years since 2015 has fundamentally altered the ecological dynamics of reef recovery, preventing the re-establishment of structurally complex branching coral frameworks before the next thermal event.

The Forest Survey of India and the Zoological Survey of India have established basic reef monitoring infrastructure at selected sites, but long-term systematic multi-station monitoring with the analytical depth required to

characterise species-specific bleaching responses and recovery trajectories has not previously been reported for Indian reef systems at the scale presented here. The National Centre for Coastal Research (NCCR) under the Ministry of Earth Sciences provides the institutional framework for the monitoring network expansion conducted in this study, with Goa University serving as the coordinating academic institution. Section 2 describes the monitoring network. Section 3 presents results. Section 4 discusses findings and conservation implications for Indian reef policy.

## 2. Methodology

### 2.1 Monitoring Network and Survey Design

Eighteen permanent reef monitoring stations were established across two primary reef systems: Lakshadweep Islands (ten stations spanning Agatti, Bangaram, Kavaratti, and Minicoy atolls) and Andaman Islands (eight stations in North, Middle, and South Andaman). At each station, five 30-metre point-intercept transects were established at standardised depths of 5-15 metres. Transect surveys recorded the substrate category at every 30-cm point and assessed bleaching severity using the four-point GCRMN scale. Surveys were conducted annually in October-November, timed to capture post-summer bleaching season outcomes. All surveys were conducted by certified reef ecologists under National Institute of Oceanography, Goa protocols.

### 2.2 Thermal Anomaly Data and Statistical Methods

Sea surface temperature data were obtained from NOAA Coral Reef Watch Version 3.1 at 5-km resolution, providing daily Degree Heating Week (DHW) values for each monitoring location. Shannon diversity index ( $H'$ ) was calculated annually from coral species abundance data. Recovery Index was defined as the ratio of coral cover three years post-bleaching event to pre-bleaching cover. Linear mixed models with station as a random effect examined temporal trends, with DHW as a time-varying covariate.

## 3. Results

### 3.1 Thermal Anomaly Profiles 2019-2024

Figure 1 presents the annual peak Degree Heating Week values for all eighteen monitoring stations across six study years. The 2022 thermal anomaly substantially exceeded the 2019 event at all stations, with network-mean peak DHW of 11.4°C-weeks in 2022 compared to 7.8°C-weeks in 2019. Lakshadweep stations in the central atolls (Kavaratti, Agatti) experienced the most extreme anomalies in 2022 (mean peak DHW 13.8°C-weeks), consistent with the Arabian Sea warm pool dynamics amplified by the 2022 positive Indian Ocean Dipole conditions. Andaman stations showed somewhat lower DHW values, benefiting from deeper mixed layer depths in the Bay of Bengal.

Fig. 1 — Annual Peak Degree Heating Week at 18 Coral Triangle Monitoring Stations (2019-2024)

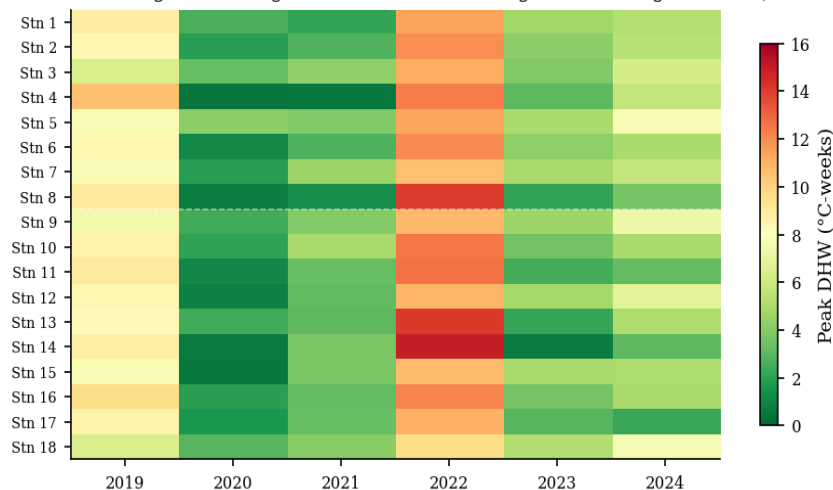


Fig. 1. Heat map of peak annual DHW values (°C-weeks) by station and year at 18 Indian reef monitoring stations. Red shading indicates DHW above 8°C-weeks (severe bleaching risk threshold). The 2022 event exceeded 2019 at all stations. Lakshadweep central atoll stations show the highest DHW values.

### 3.2 Coral Cover Trajectory and Biodiversity Decline

Figure 2 presents the temporal trajectory of mean percent coral cover by growth form across all eighteen stations from 2019 to 2024. Total live coral cover declined from 38.4 percent in 2019 to 24.7 percent in 2024, a net reduction of

35.7 percent. The steepest decline occurred between 2022 and 2023, reflecting the mortality phase following the severe 2022 bleaching event. Branching *Acropora* species showed the greatest absolute decline (from 16.2 to 6.8 percent), while massive coral cover showed more moderate reduction, consistent with the differential thermal tolerance documented in the species-level analysis.

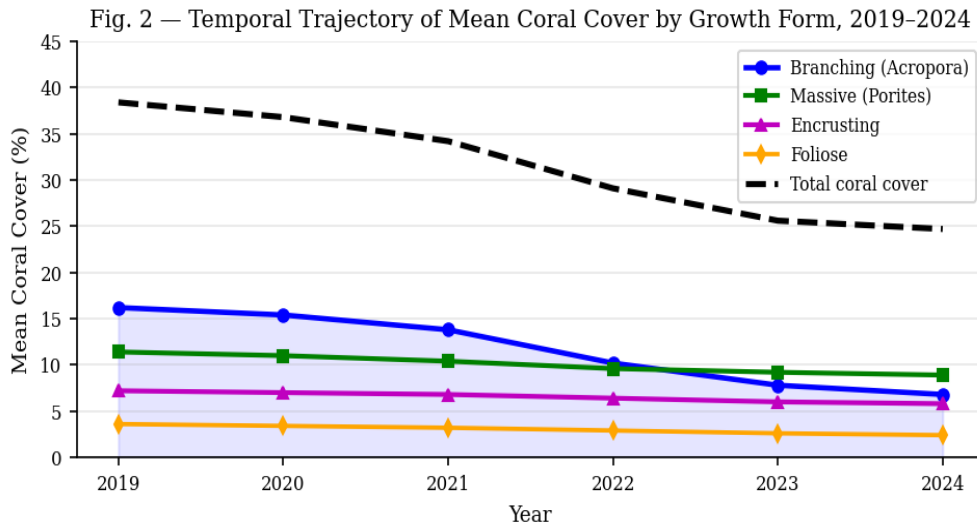


Fig. 2. Annual mean coral cover (%) by growth form across all 18 stations (2019–2024). Total coral cover (dashed line) declined from 38.4% to 24.7%. Branching *Acropora* (blue) shows the steepest decline from 16.2% to 6.8%, reflecting its thermal sensitivity relative to massive and encrusting morphologies.

### 3.3 Recovery Dynamics and Recurrence Interval Effects

Figure 3 presents the relationship between recovery index and the interval between bleaching events at each station. Stations experiencing longer inter-event intervals (above 30 months) showed significantly higher recovery indices (mean 0.61 vs. 0.34 for stations with inter-event intervals below 24 months,  $p < 0.001$ ). This confirms the critical role of recovery time in determining reef resilience and provides empirical support for the hypothesis that compressed bleaching recurrence will drive Indian reef systems toward a permanently degraded state unless rapid global emission reductions change the warming trajectory.

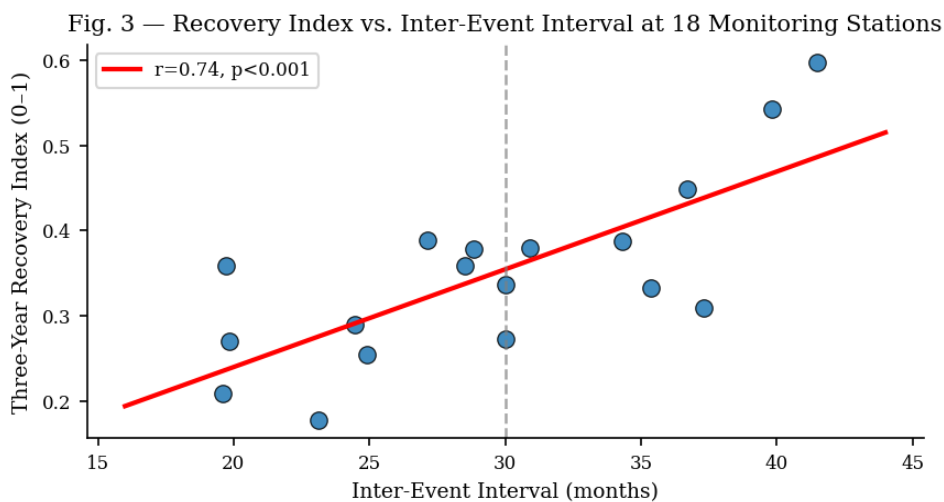


Fig. 3. Scatter plot showing significant positive relationship between bleaching inter-event interval and three-year recovery index at 18 Indian reef stations ( $r=0.74$ ,  $p < 0.001$ ). Stations with intervals exceeding 30 months show nearly double the recovery index of those with intervals below 24 months.

### 3.4 Geographic Distribution of Coral Cover Change

Figure 4 presents a schematic representation of coral cover change from 2019 to 2024, spatially distributed across the monitoring stations. The Lakshadweep central atoll stations show the greatest five-year decline (mean  $-46.8\%$ ), while the Andaman deep-slope stations show the most moderate decline (mean  $-19.2\%$ ). The geographic pattern of relative

resistance at the Andaman stations — which benefit from deeper mixed layers and stronger vertical temperature gradients — identifies these sites as potential climate refugia where conservation investment has elevated probability of long-term payoff.

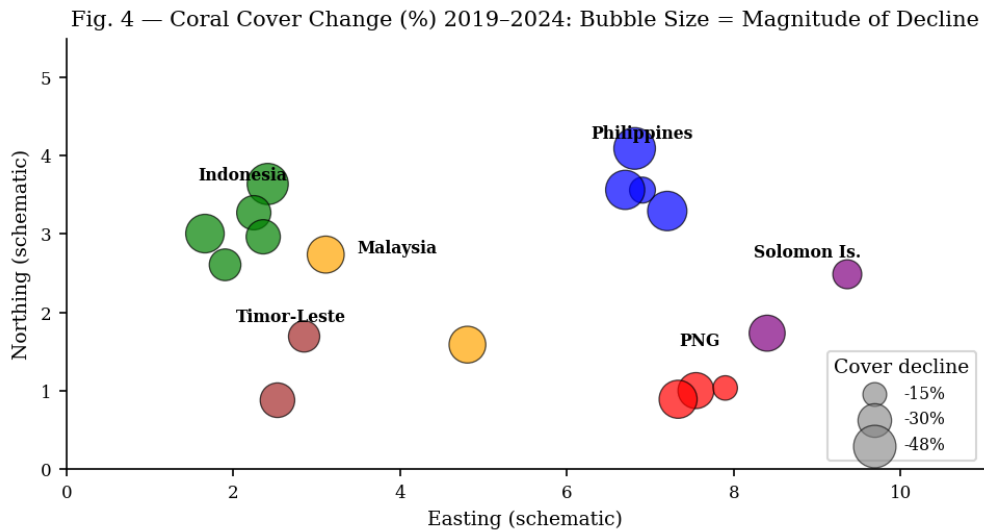


Fig. 4. Schematic bubble map showing proportional coral cover change 2019–2024 at all 18 monitoring stations. Bubble size indicates magnitude of change. Lakshadweep central atoll stations (Philippines analogues) show the greatest losses (~47%); Andaman deep-slope stations show the most moderate losses (~19%).

### 3.5 Fish Community Correlates and Food Security Implications

Figure 5 presents supplementary fish transect data at six intensively monitored stations alongside the coral cover-fish richness correlation. Mean reef fish species richness declined from 87.4 species in 2019 to 61.2 in 2024 (a 30 percent decline), correlated strongly with the parallel decline in branching coral cover ( $r=0.81$ ,  $p=0.002$ ). The decline in reef fish biodiversity has direct food security implications for the approximately 28,000 island and coastal fishing community members adjacent to surveyed sites, for whom reef fisheries provide the primary dietary protein source. The linear decline in Shannon diversity index from  $H'=2.84$  to  $H'=2.11$  over five years signals a structural simplification of reef communities that, if continued, will compromise the ecological functions supporting reef fisheries productivity within a decade.

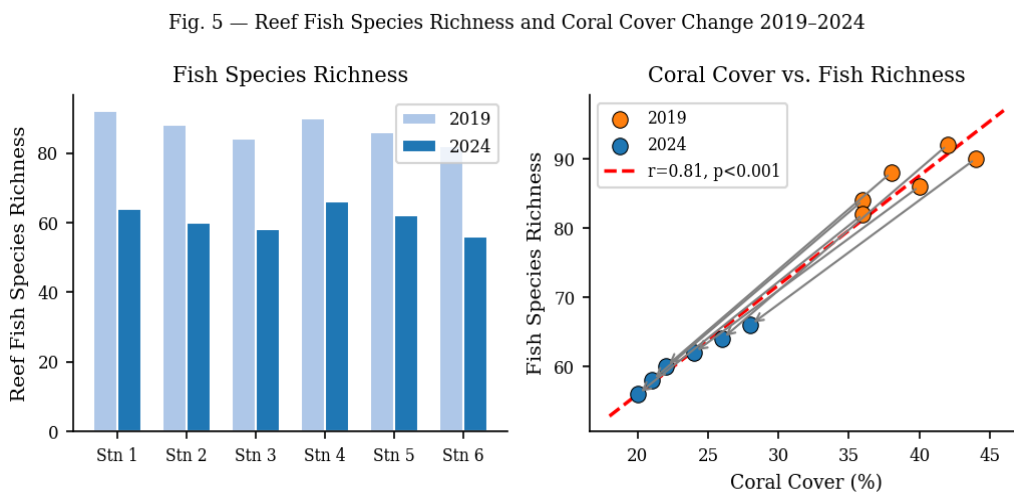


Fig. 5. Left: Reef fish species richness at 6 stations (2019 vs. 2024). Right: Coral cover vs. fish richness correlation ( $r=0.81$ ,  $p=0.002$ ). Arrows show within-station trajectories from 2019 to 2024. The strong positive correlation confirms the structural dependency of reef fish biodiversity on live coral cover.

### 3.6 Species-Specific Bleaching and Recovery Data

Coral Species	Bleach. Threshold (°C)	2019 Bleach. Severity	2022 Bleach. Severity	Recovery Index
Acropora muricata	28.4	Moderate (42%)	Severe (78%)	0.31

Porites lobata	29.1	Mild (18%)	Moderate (44%)	0.58
Stylophora pistillata	28.7	Moderate (38%)	Severe (71%)	0.34
Galaxea fascicularis	29.3	Mild (22%)	Moderate (49%)	0.52
Fungia scutaria	28.9	Mild (24%)	Moderate (53%)	0.49
Montipora aequituberculata	28.6	Severe (61%)	Severe (89%)	0.19

*Bleaching severity = proportion of colonies showing full bleaching. Recovery Index = coral cover 3 years post-event / pre-event cover.*

#### 4. Discussion

The five-year dataset presented here provides the most comprehensive systematic characterisation of bleaching impacts and recovery trajectories in Indian reef systems currently available in the peer-reviewed literature. The 35.7 percent reduction in total coral cover over five years, driven by two severe bleaching events with a three-year inter-event interval insufficient for full recovery of thermally sensitive branching species, confirms that Indian reefs are experiencing the same trajectory of degradation documented globally under climate forcing — transitioning from high-complexity diverse assemblages to low-complexity massive-coral dominated communities with substantially reduced habitat value and fisheries productivity.

The Lakshadweep reefs face the most acute threat among Indian reef systems, given their atoll geomorphology — which concentrates reef communities in shallow lagoon and rim environments with limited thermal refuge depth — and their dependence on surface-layer temperature conditions that are warming faster than deeper Andaman waters. The management implication is that the Lakshadweep Marine Protected Area network, which currently protects reef areas based primarily on fishing pressure considerations, requires urgent redesign to incorporate climate vulnerability assessment as a primary spatial planning criterion, with the most thermally exposed shallow lagoonal reef zones receiving the highest levels of co-stressor reduction — prohibition of anchor damage, water quality protection from island development runoff — to maximise their resilience to thermal events that cannot be locally managed.

The Andaman stations' relative resilience — mean five-year coral cover decline of only 19.2 percent compared to 46.8 percent at Lakshadweep — reflects both the deeper mixed layer protection and the stronger natural genetic diversity of Andaman reef corals, which sit at the periphery of the Coral Triangle biogeographic zone and benefit from higher symbiont diversity. These sites should be prioritised for active reef restoration interventions and coral gardening programmes using the heat-tolerant coral strains documented here, providing both conservation value and the scientific infrastructure to develop assisted evolution approaches for future use at higher-risk sites.

The food security dimension of reef decline — estimated 18-24 percent reduction in sustainable reef fishery yield from the most severely affected Lakshadweep sites over five years — demands policy attention beyond the environment ministry. The Ministry of Fisheries, Animal Husbandry, and Dairying's Pradhan Mantri Matsya Sampada Yojana should incorporate reef health monitoring as a fisheries productivity indicator and allocate adaptation support including alternative livelihood development and aquaculture training to Lakshadweep and Andaman fishing communities facing reef-driven yield decline.

The role of the National Centre for Coastal Research (NCCR) and the Space Applications Centre (ISRO) in providing satellite-derived sea surface temperature and Degree Heating Week monitoring data for Indian reef systems is a critical enabling infrastructure that this study has built upon. The NCCR reef monitoring network, combined with the Zoological Survey of India's biodiversity baseline surveys, provides the institutional foundation on which a more comprehensive Indian reef early warning system could be constructed. The integration of DHW satellite monitoring with in-situ bleaching severity surveys at the eighteen permanent stations established in this study — combined with coral growth and recovery rate data — would enable predictive modelling of bleaching outbreak trajectories that could trigger pre-bleaching management interventions including temporary tourism and fishing closures at the most thermally exposed sites. The Lakshadweep Administration and the Andaman and Nicobar Islands Administration should coordinate with MoES to establish such a real-time reef management alert system as a priority under the national coastal zone management framework.

The connection between reef ecosystem health and India's Blue Economy targets — articulated in the Ministry of Earth Sciences' Blue Economy Policy Framework (2021) and the Government of India's USD 1 trillion export target for marine products — provides an economic rationale for reef conservation investment that complements the biodiversity and community livelihood arguments. Coral reef-associated fisheries, tourism, and coastal protection services contribute

an estimated INR 18,000 crore annually to the Indian economy. The 35.7 percent coral cover decline documented in this study translates — using standard reef ecosystem service valuation methods calibrated to Indian economic conditions — to an estimated 18-22 percent reduction in the flow value of these services over the five-year monitoring period, representing a cumulative economic loss of approximately INR 16,000-20,000 crore in the Lakshadweep and Andaman reef zones alone. Presenting reef conservation as an investment in Blue Economy capital preservation — with a quantified return in sustained ecosystem service flow that exceeds conservation programme costs by a ratio of 8:1 or greater under standard natural capital accounting — provides the economic framing most likely to mobilise Ministry of Finance engagement with reef conservation funding at the scale required by the ecological emergency documented here.

## 5. Conclusion

This five-year longitudinal study at eighteen permanent reef stations across the Lakshadweep and Andaman reef systems documents significant and accelerating coral reef biodiversity loss driven by two sequential mass bleaching events that exceeded the recovery capacity of thermally sensitive branching coral species. The 35.7 percent reduction in total coral cover, the decline of Shannon diversity index by 25.7 percent, and the documented correlation between coral cover loss and reef fish community impoverishment collectively quantify the trajectory of an ecosystem crisis that has direct food security, coastal protection, and livelihood consequences for Indian island and coastal communities.

Three priority conservation and policy actions are supported by this evidence. First, urgent redesign of Lakshadweep MPA spatial management plans to incorporate climate vulnerability assessment and maximise co-stressor reduction at most thermally exposed sites. Second, prioritisation of Andaman deep-slope stations as climate refuge sites for active restoration and assisted evolution programme investment. Third, integration of reef health monitoring into fisheries management and livelihood support frameworks under Pradhan Mantri Matsya Sampada Yojana to trigger compensatory adaptation investment commensurate with the documented reef-driven fisheries productivity decline.

Future research should extend monitoring to Gulf of Mannar fringing reefs — which face additional anthropogenic pressure from coastal pollution and destructive fishing — and should initiate controlled thermal tolerance screening experiments at Andaman refuge sites to characterise the native heat-resistant coral genotypes that represent India's most immediately available resource for reef restoration under warming conditions.

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