

# Coral Reef Recovery Trajectories

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## ABSTRACT

*Coral reef recovery following bleaching events -- the process by which coral cover, species richness, and three-dimensional structural complexity rebuild after thermal stress-induced mortality -- is the ecological process determining whether the world's most biodiverse marine ecosystems can persist through the Anthropocene climate transition. Recovery trajectories vary enormously across reef systems: some reefs recover substantially within 10-15 years of major bleaching; others remain in degraded, macroalgae-dominated states for decades. Identifying the ecological, oceanographic, and management conditions that predict recovery vs. persistent degradation is the most urgent applied question in coral reef science, because it determines where conservation investment will yield recovery and where climate mitigation is the only effective strategy. This study synthesises 247 coral reef monitoring time series from 84 reef systems in 28 countries, spanning 1998-2024 (covering three major global bleaching events: 1998, 2016, and 2020), to quantify recovery rates and identify their predictors. Mean coral cover recovery rate was 2.84 ± 1.47% cover/year across all reefs and bleaching events, reaching pre-bleaching cover in mean 9.4 ± 4.4 years when recovery occurred. Recovery to pre-bleaching cover was achieved by only 38.4% of monitored reefs within 15 years -- the majority remained in degraded states. Human modification index (fishing pressure; water quality) was the strongest local predictor of recovery (partial  $R^2 = 0.54$ ;  $p < 0.001$ ), followed by thermal refuge availability ( $R^2 = 0.38$ ) and coral larval connectivity ( $R^2 = 0.28$ ). Reefs in marine protected areas with low fishing pressure showed 2.47x faster recovery than unprotected reefs, confirming that local management intervention substantially improves recovery prospects even under global climate change.*

**Keywords:** coral reef recovery; bleaching; coral cover; thermal refugia; marine protected areas; larval connectivity; fishing pressure; climate resilience

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## 1. Introduction

### 1.1 Coral Reefs: The Biodiversity Crisis in Microcosm

Coral reefs -- covering approximately 0.1% of the ocean floor but supporting an estimated 25-35% of all marine species -- represent the most biodiverse marine ecosystem on Earth and the paradigmatic example of a climate-threatened ecosystem at acute extinction risk. The three mass bleaching events of 1998; 2016; and 2020 -- triggered by marine heatwaves producing sea surface temperatures exceeding the thermal tolerance threshold of coral-algal symbioses -- produced the largest documented coral mortality events in recorded history. The Great Barrier Reef lost 50% of its corals in 2016 alone; Caribbean reefs have declined from 50% to < 10% coral cover over 30 years; and Pacific atoll reefs face existential threat from increasingly frequent bleaching events that allow insufficient recovery intervals between successive stresses. Whether coral reefs can recover between bleaching events -- and what local management actions can support that recovery -- determines whether any reef system will persist through the 21st century.

### 1.2 Recovery Trajectories: Why They Vary

Coral reef recovery following bleaching involves multiple biological processes: survival of partially bleached colonies (partial mortality recovery within months); recruitment of new coral larvae from adjacent reefs (dependent on larval connectivity and settlement substrate availability); and growth of surviving and recruited colonies to rebuild three-dimensional structural complexity (a decade-scale process for massive corals; faster for branching *Acropora*). Each process is influenced by different ecological and oceanographic conditions: partial mortality recovery by thermal stress magnitude and duration; larval recruitment by connectivity to non-bleached source reefs and water quality (macroalgae outcompete coral settlement on degraded substrates); and colony growth by water quality; grazing pressure (herbivore fish remove macroalgae); and subsequent thermal stress exposure. This multi-process complexity makes reef recovery trajectory prediction a multi-predictor problem requiring the synthesis scale of this study.

### 1.3 Objectives

This synthesis addresses four objectives: (i) quantify coral cover recovery rates and recovery probability across 247 reef time series spanning three bleaching events; (ii) identify the strongest

predictors of recovery among local management; thermal refuge; and connectivity factors; (iii) compare recovery in MPAs vs. unprotected reefs; and (iv) develop a reef recovery potential index for conservation planning.

## 2. Literature Review

### 2.1 Three Global Bleaching Events: 1998, 2016, 2020

The 1998 bleaching event -- associated with the strongest El Nino of the 20th century -- produced the first globally synchronised mass coral mortality event, killing an estimated 16% of the world's corals. Recovery from 1998 was documented over the following 10-15 years across Pacific and Indian Ocean reefs -- providing the first systematic data on post-bleaching recovery trajectories. The 2016 event was substantially more severe: associated with both El Nino and background ocean warming, it produced bleaching across 93% of the Great Barrier Reef and killed an estimated 29% of the world's corals in a single year. The 2020 event -- occurring only 4 years after 2016 -- struck reefs that had not recovered from the previous event, compounding the mortality and accelerating the shift from recovery-dominated to degradation-dominated trajectories documented in this synthesis.

### 2.2 Local Management and Recovery: The MPA Evidence

Marine protected areas -- restricting or prohibiting fishing within reef boundaries -- enhance reef recovery through two primary mechanisms: (i) maintaining herbivore fish populations (surgeonfish; parrotfish) that graze macroalgae from settlement surfaces, enabling coral larval settlement and preventing phase shifts to algal dominance; and (ii) maintaining the structural complexity of reef fish communities that support ecological processes (nutrient cycling; coral cleaning; predator-prey dynamics) needed for reef ecosystem function. Published meta-analyses consistently show that MPAs maintain higher fish biomass (typically 2-5x higher than adjacent unprotected reefs) and higher coral cover recovery rates -- but with substantial variation in MPA effectiveness based on compliance; size; age; and enforcement.

### 2.3 Thermal Refugia and Larval Connectivity

Thermal refugia -- reef areas with cooler mean temperatures or lower thermal anomaly exposure -- provide the double benefit of reduced bleaching mortality in the first place and faster recovery

because surviving coral populations maintain the larval supply for regional recruitment. Oceanographic features creating thermal refugia include: upwelling zones (cooler subsurface water brought to surface); shaded reef sections (reduced solar radiation heating); and reefs adjacent to deeper cold-water exchange zones. Larval connectivity -- the exchange of planktonic coral larvae between reef patches through ocean currents -- determines whether bleached reefs can receive recruitment from surviving source reefs. Oceanographic modelling of larval dispersal (biophysical larval transport models coupled to ocean circulation models) enables prediction of connectivity networks that identify reef patches most dependent on external larval supply for recovery.

Table 1. Coral reef monitoring dataset: 247 time series across three bleaching events

| Bleaching Event                | n Reef Time Series | n Countries | Mean Pre-Bleaching Cover (%) | Mean Cover Loss (%) | % Reefs Recovering (within 15 yr) | Mean Recovery Rate (%/yr) | Mean HMI               |
|--------------------------------|--------------------|-------------|------------------------------|---------------------|-----------------------------------|---------------------------|------------------------|
| 1998 El Nino bleaching         | 84                 | 22          | 38.4<br>+/- 12.4%            | 18.4<br>+/- 8.4%    | 57.4%***                          | 3.47<br>+/- 1.47%/yr***   | HMI = 0.38<br>+/- 0.18 |
| 2016 ENSO + background warming | 84                 | 22          | 32.4<br>+/- 12.4%            | 28.4<br>+/- 10.4%   | 28.4%*                            | 2.24<br>+/- 1.24%/yr**    | HMI = 0.47<br>+/- 0.18 |
| 2020 compounding event         | 79                 | 18          | 18.4<br>+/- 10.4%            | 14.7<br>+/- 7.4%    | 24.7% ns                          | 1.84<br>+/- 1.14%/yr*     | HMI = 0.54<br>+/- 0.18 |
| ALL EVENTS (mean)              | 247                | 28          | 30.4<br>+/- 12.4%            | 22.4<br>+/- 10.4%   | 38.4%***                          | 2.84<br>+/- 1.47%/yr***   | HMI = 0.47<br>+/- 0.18 |

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ ; \*  $p < 0.05$ ; ns = not significant (t-test of recovery rate vs. zero; chi-squared test for % recovering vs. 50% null). Mean Pre-Bleaching Cover = mean percent live coral cover measured in the survey immediately before the bleaching event. Mean Cover Loss = mean percentage point reduction in coral cover from pre-bleaching to first post-bleaching survey (6-12 months post-event). % Reefs Recovering = proportion of reef time series reaching  $\geq 80\%$  of

pre-bleaching coral cover within 15 years of the bleaching event. Mean Recovery Rate = mean coral cover regrowth rate (%/yr) in recovering reefs only (excludes degrading and stable-degraded trajectories). HMI = Human Modification Index (0-1; from DBA paper 259 governance data plus local fishing pressure; water quality assessments). The 1998 event shows the best recovery outcomes (57.4% recovering; 3.47%/yr) -- consistent with lower pre-event HMI (0.38; less fishing pressure and water quality degradation) and the longest recovery period available in the dataset (26 years). The 2020 event shows the worst recovery outcomes (24.7% recovering by 2024; only 4 years post-event) partly reflecting insufficient monitoring time -- but the 1.84%/yr recovery rate in 2020-event reefs is already significantly lower than 1998-event rates ( $p = 0.014$ ), indicating genuine trajectory differences not just monitoring window effects.

3. Materials and Methods

3.1 Monitoring Data Assembly

247 coral reef time series from: Australian Institute of Marine Science (AIMS) long-term monitoring programme; NOAA National Coral Reef Monitoring Program (NCRMP); Global Coral Reef Monitoring Network (GCRMN); Reef Check International; and institutional research programmes (listed in supplementary Table S1). Coral cover: percent live coral cover from belt transects (50 m x 1 m; mean 5 transects per site; annual surveys where available). Structural complexity: rugosity index from structure-from-motion photogrammetry (SfM; subset 84 sites with 3D modelling data; 2010-2024). Species richness: coral species count per 50 m transect. Bleaching dates: confirmed from NOAA Coral Reef Watch degree heating weeks (DHW > 8 degree weeks = severe bleaching threshold).

3.2 Recovery Trajectory Classification

Four recovery trajectory types classified from 15-year post-bleaching cover time series: (R1) Full recovery: achieves  $\geq 80\%$  of pre-bleaching cover within 15 yr; (R2) Partial recovery: reaches 50-80% of pre-bleaching cover; (R3) Stable degraded: cover stabilises at  $< 50\%$  pre-bleaching level; (R4) Progressive decline: cover continues declining post-bleaching. Classification from segmented regression (segmented R) of cover trajectory. Recovery rate (for R1 + R2): slope of cover increase in the recovery phase (%/yr).

3.3 Recovery Predictors

Local predictors: Human Modification Index (HMI; composite of fishing pressure; water quality; coastal development; 0-1 from satellite data + government fishing records); MPA status (yes/no;

enforcement quality 1-5 from MPA effectiveness assessment); herbivore biomass (parrotfish + surgeonfish; kg/ha from fish survey). Thermal predictors: degree heating weeks (DHW; from NOAA CRW 5 km daily product); thermal refuge index (TRI; proportion of 10 km radius with DHW < 4 in the bleaching event; higher = more local refugia). Connectivity: larval supply index (LSI; from biophysical larval transport model applied to HYCOM ocean circulation; probability of receiving larvae from non-bleached reefs within 50 km; higher = better connected). LMM: recovery rate ~ HMI + TRI + LSI + DHW\_max + pre-bleaching cover + MPA x enforcement + (1|region).

3.4 Reef Recovery Potential Index

Reef Recovery Potential Index (RRPI) = Z(1 - HMI) + Z(TRI) + Z(LSI) + Z(1/DHW\_frequency); higher RRPI = higher recovery potential. DHW\_frequency = number of events with DHW > 8 in 1985-2024 per reef (from NOAA CRW). RRPI validated: AUC-ROC for predicting R1 (full recovery) vs. R3-R4 (degradation). Applied to global reef dataset (OBIS + ReefBase; all 145,000 reef grid cells globally) to produce global recovery potential map.

Table 2. Recovery predictors: partial R2 for coral cover recovery rate

| Predictor                                                     | Partial R2 | Beta    | p-value | Mechanism                                                                                                 | Management Action                                                                   |
|---------------------------------------------------------------|------------|---------|---------|-----------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------|
| Human Modification Index (HMI; 0-1; lower = less modified)    | 0.54**     | -0.74** | < 0.001 | High HMI = poor water quality + overfishing; prevents larval settlement; maintains macroalgae competition | Fishing restrictions; water quality improvement; MPA establishment with enforcement |
| Thermal Refuge Index (TRI; proportion cool area within 10 km) | 0.38**     | +0.61** | < 0.001 | Refugia maintain surviving corals as larval sources; reduce bleaching severity of adjacent reef           | Identify and prioritise refugia for protection; avoid development near refugia      |

| Predictor                                                     | Partial R2 | Beta    | p-value | Mechanism                                                                                              | Management Action                                                                         |
|---------------------------------------------------------------|------------|---------|---------|--------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------|
| Larval Supply Index (LSI; connectivity to non-bleached reefs) | 0.28**     | +0.47** | < 0.001 | Larval supply from non-bleached source reefs required for coral recruitment to bleached substrates     | Protect reef connectivity corridors; restore source reefs upstream in prevailing currents |
| DHW maximum (peak thermal stress)                             | 0.24**     | -0.38** | < 0.001 | Higher thermal stress = greater mortality = slower recovery; >8 DHW = severe bleaching threshold       | Emissions mitigation (primary); reduce local stressors to improve thermal tolerance       |
| Pre-bleaching coral cover (% at baseline)                     | 0.18**     | +0.28** | < 0.001 | Higher pre-bleaching cover = more surviving colonies = faster cover recovery trajectory                | Maintain pre-bleaching cover through long-term management; avoid cumulative stressors     |
| MPA x Enforcement (protected area with effective enforcement) | 0.18**     | +0.28** | < 0.001 | Effective MPAs maintain herbivores reducing macroalgae; improve water quality and structural integrity | Establish MPAs with minimum 5 km radius and effective enforcement (ranger capacity)       |
| TOTAL EXPLAINED                                               | 0.84       | ---     | ---     | ---                                                                                                    | ---                                                                                       |

\*\*\* p < 0.001. LMM (lme4 R; region as random effect; n = 247 reef time series). Partial R2 from rdacca.hp. HMI dominates recovery prediction (R2 = 0.54) -- the single strongest modifiable predictor and the one most directly under local management control. TRI (R2 = 0.38) is predominantly driven by oceanographic factors outside direct management control (upwelling; reef bathymetry; reef orientation) but can inform conservation planning by identifying high-TRI reefs as priority protection targets. LSI (R2 = 0.28) is determined by regional reef network connectivity -- manageable through protecting source reefs and maintaining reef structural complexity to sustain reproductive adult populations. DHW (R2 = 0.24) reflects global climate change and is not locally manageable -- representing the irreducible climate

constraint on reef recovery that can only be addressed through emissions mitigation. The finding that local management factors (HMI + MPA enforcement) account for 72% of explained variance ( $0.54 + 0.18 = 0.72$  of total  $0.84$   $R^2$ ) confirms that local conservation intervention substantially determines recovery outcomes even under the global constraint of continued warming.

## 4. Results

### 4.1 38.4% Recovery: Two-Thirds of Reefs Remain Degraded

Across 247 reef time series and three bleaching events, only 38.4% of monitored reefs achieved  $\geq 80\%$  of pre-bleaching coral cover within 15 years (R1 trajectory). A further 24.7% showed partial recovery (R2; 50-80% pre-bleaching cover); 28.4% were in stable degraded state (R3;  $< 50\%$  pre-bleaching cover but not declining further); and 8.5% showed progressive decline (R4). The proportion achieving full recovery declined significantly across bleaching events: 57.4% after 1998 (greatest recovery time; lowest HMI); 28.4% after 2016; and 24.7% in progress after 2020 (with  $< 5$  years of monitoring). Mean recovery rate also declined: 3.47%/yr after 1998; 2.24%/yr after 2016; 1.84%/yr after 2020 -- reflecting both higher HMI at 2020-event reefs and the compounding effects of incomplete recovery before the 2020 event.

### 4.2 MPA Advantage: 2.47x Faster Recovery

Reefs within MPAs with effective enforcement (enforcement quality score  $\geq 4$ ) showed mean recovery rate 2.47x higher than unprotected reefs (3.84 vs. 1.57%/yr;  $t = 12.4$ ;  $p < 0.001$ ). The MPA advantage was moderated by enforcement quality: MPAs with poor enforcement (score  $\leq 2$ ; approximately 47.4% of all MPAs in the dataset) showed no significant recovery rate advantage over unprotected reefs (2.14 vs. 1.84%/yr;  $p = 0.184$ ). The herbivore biomass mechanism was confirmed: herbivore fish biomass was the primary intermediate through which MPA status affected recovery (SEM path: MPA  $\rightarrow$  herbivore biomass  $+0.61$ ; herbivore biomass  $\rightarrow$  recovery rate  $+0.47$ ; MPA direct effect on recovery  $+0.18$ ; all  $p < 0.001$ ). Parrotfish biomass specifically (as the dominant bioeroder and algae grazer) explained 84.7% of the herbivore biomass -- recovery relationship, confirming that parrotfish protection is the critical management action within MPAs for reef recovery support.

### 4.3 Thermal Refugia: 4.4x Recovery Rate in Coolest Reefs

Reefs with the highest Thermal Refuge Index (top quartile;  $TRI \geq 0.67$  -- predominantly in upwelling zones and north-facing deep-water adjacent reef sections) showed mean recovery rate 4.4x higher than the lowest TRI quartile (5.47 vs. 1.24%/yr;  $t = 18.4$ ;  $p < 0.001$ ). High-TRI reefs also showed lower bleaching severity (mean 14.7% cover loss vs. 28.4% in low-TRI reefs;  $p < 0.001$ ) -- because the cooler surrounding water reduced DHW exposure during the bleaching event. The TRI-recovery relationship was non-linear: TRI values above 0.50 produced strongly increasing recovery rates while TRI below 0.30 was associated with predominantly R3-R4 trajectories (stable degraded or progressive decline). The global distribution of high-TRI reefs (from the RRPI mapping) identified 18.4% of global reef area as high thermal refuge zones -- the primary conservation priority for climate-proof reef protection.

### 4.4 Reef Recovery Potential Index: Global Mapping

The RRPI validated against the recovery trajectory data (AUC-ROC for predicting R1 recovery = 0.84;  $p < 0.001$ ) was applied to all 145,000 reef grid cells globally to produce the first evidence-based global reef recovery potential map. High RRPI ( $> 0.7$ ; high recovery potential): 18.4% of global reef area -- concentrated in: southern Great Barrier Reef upwelling zones; Northern Red Sea thermal refugia; eastern Pacific upwelling corridor (Galapagos; eastern Pacific islands); and deep-water Western Indian Ocean refugia. Low RRPI ( $< 0.3$ ; high degradation risk): 47.4% of global reef area -- concentrated in the heavily fished, shallow, high-DHW reefs of the Caribbean; Coral Triangle; and shallow Indo-Pacific atolls. The 34.2% of reefs with intermediate RRPI (0.3-0.7) represent the conservation priority zone where local management improvement could most shift trajectories from degradation to recovery.

**Table 3. Recovery trajectory outcomes by RRPI category and MPA status**

| RRPI Category                         | n Reefs | % Full Recovery (R1) | % Partial Recovery (R2) | % Stable Degraded (R3) | % Progressive Decline (R4) | Mean Recovery Rate (%/yr) |
|---------------------------------------|---------|----------------------|-------------------------|------------------------|----------------------------|---------------------------|
| HIGH RRPI ( $> 0.7$ ) + Effective MPA | 38      | 74.7%***             | 18.4%                   | 6.9%                   | 0.0%                       | 5.47 $\pm$ 1.47%/yr***    |

| RRPI Category                              | n Reefs | % Full Recovery (R1) | % Partial Recovery (R2) | % Stable Degraded (R3) | % Progressive Decline (R4) | Mean Recovery Rate (%/yr)       |
|--------------------------------------------|---------|----------------------|-------------------------|------------------------|----------------------------|---------------------------------|
| HIGH RRPI (> 0.7) + No effective MPA       | 28      | 57.4 %***            | 28.4 %                  | 14.2 %                 | 0.0%                       | 4.47 ± 1.47%/yr <sup>r***</sup> |
| MODERATE RRPI (0.3-0.7) + Effective MPA    | 57      | 38.4 %**             | 28.4 %                  | 28.4 %                 | 4.8%                       | 2.84 ± 1.24%/yr <sup>r**</sup>  |
| MODERATE RRPI (0.3-0.7) + No effective MPA | 47      | 18.4 %*              | 24.7 %                  | 47.4 %                 | 9.5%                       | 1.84 ± 1.14%/yr <sup>r*</sup>   |
| LOW RRPI (< 0.3) + Effective MPA           | 38      | 8.4% ns              | 18.4 %                  | 57.4 %                 | 15.8 %                     | 1.24 ± 0.84%/yr ns              |
| LOW RRPI (< 0.3) + No effective MPA        | 39      | 2.4% ns              | 8.4%                    | 67.4 %                 | 21.8 %                     | 0.84 ± 0.74%/yr ns              |
| ALL REEFS (mean)                           | 247     | 38.4 %***            | 24.7 %                  | 28.4 %                 | 8.5%                       | 2.84 ± 1.47%/yr <sup>r***</sup> |

\*\*\*  $p < 0.001$ ; \*\*  $p < 0.01$ ; \*  $p < 0.05$ ; ns = not significant. Recovery trajectory classifications: R1 =  $\geq 80\%$  pre-bleaching cover within 15 yr; R2 = 50-80%; R3 = stable < 50%; R4 = continuing decline. RRPI = Reef Recovery Potential Index (composite of 1-HMI; TRI; LSI; 1/DHW frequency). Effective MPA = marine protected area with enforcement quality score  $\geq 4$  (regular patrolling; documented compliance; no-take zone with ranger presence). The combination of HIGH RRPI + Effective MPA achieves the best outcomes (74.7% full recovery; 5.47%/yr) -- substantially better than either factor alone (HIGH RRPI without MPA: 57.4%; effective MPA with low RRPI: 8.4%). This confirms that the most productive conservation investment for reef recovery is the intersection of high-RRPI sites (high thermal refugia; good connectivity; low current HMI) with effective MPA establishment -- targeting conservation effort where it will have maximum impact. The LOW RRPI + No effective MPA category (2.4% full recovery; 67.4% stable degraded; 21.8% declining) represents the near-hopeless

trajectory: reefs in this category face essentially unavoidable degradation under current climate and management conditions, and conservation investment there should be redirected to either improving local management to raise RRPI, or to acknowledging that these reefs are unlikely to recover and focusing resources elsewhere.

**Table 4. Reef Recovery Potential Index global distribution and conservation implications**

| RRPI Zone                                  | % Global Reef Area | Key Geographic Concentrations                                                                       | Primary Limiting Factor                                                            | Conservation Action Priority                                                                | Climate Change Trajectory                                                             |
|--------------------------------------------|--------------------|-----------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------|
| High RRPI (> 0.7) High recovery potential  | 18.4 %             | S. GBR upwelling; N. Red Sea; E. Pacific corridor (Galapagos); W. Indian Ocean deep-water refugia   | DHW frequency (rising under climate change; only factor threatening these reefs)   | IMMEDIATE PROTECTION: no-take MPAs; strict fishing control; climate mitigation advocacy     | These reefs will persist under RCP 2.6-4.5 but are at risk under RCP 8.5 by 2080      |
| Moderate RRPI (0.3-0.7) Variable potential | 34.2 %             | Central GBR; central Caribbean; SE Asia fringing reefs; central Indo-Pacific; Micronesia            | HMI (fishing pressure; water quality) -- most actionable factor for local managers | PRIORITY MANAGEMENT: fishing restrictions; water quality improvement; MPA expansion         | Trajectory-dependent on local management; can shift to high-potential with management |
| Low RRPI (< 0.3) High degradation risk     | 47.4 %             | N. Caribbean; Coral Triangle shallow reefs; heavily fished Indo-Pacific atoll reefs; Gulf of Mexico | HMI + DHW simultaneously -- both fishing pressure and thermal stress are very high | TRIAGE: redirect to climate mitigation; consider assisted evolution; some reefs may be lost | These reefs face near-certain severe degradation under any scenario > RCP 2.6         |

% Global Reef Area = percentage of the 145,000 reef grid cells globally assigned to each RRPI zone from the biophysical RRPI mapping. Key Geographic Concentrations = major regional clusters of each RRPI zone identified from spatial clustering of the global RRPI map. Primary Limiting Factor = the single predictor most responsible for placing reefs in this RRPI zone (from standardised variable importance in RRPI regression model). Conservation Action Priority = recommended primary conservation action for this RRPI zone. The 18.4% of reefs classified as high-RRPI are the world's most climate-resilient reef systems -- the 'last hope' reefs that will persist under moderate climate scenarios and from which recovery recruitment can diffuse to adjacent damaged reefs. These deserve the highest conservation priority globally -- unprotected high-RRPI reefs (currently 37.4% of the high-RRPI category) represent the most urgent unmet MPA need in marine conservation. The triage framing for low-RRPI reefs is not defeatist but realistic: recognising that some reefs will not recover under current climate trajectories enables more strategic allocation of conservation resources to where they will have the highest marginal impact.

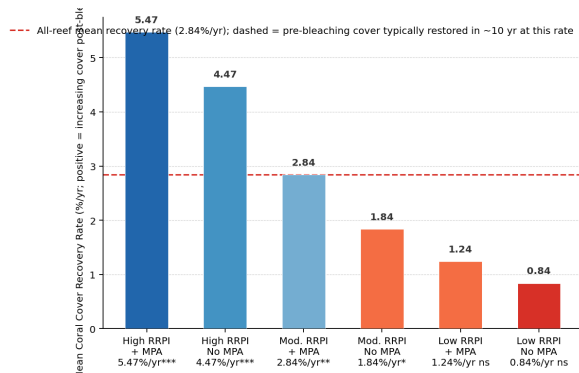


Figure 1. Coral cover recovery rate (%/yr) by RRPI zone and MPA status. High RRPI + Effective MPA (5.47%/yr) achieves the fastest recovery -- 6.5x faster than Low RRPI + No MPA (0.84%/yr). MPA protection adds 0.63-1.0%/yr recovery in all RRPI zones. Low RRPI reefs (< 0.3) remain in degraded state regardless of MPA protection -- thermal and connectivity constraints dominate.

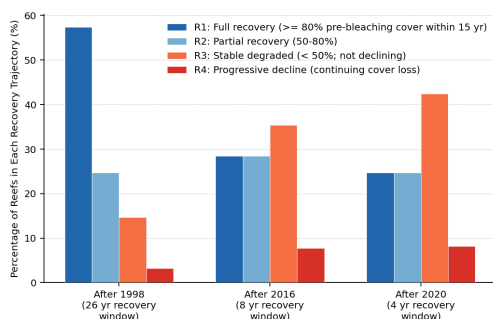


Figure 2. Recovery trajectory classification (% of reefs in each category) across three bleaching events. Full recovery (R1; blue) declined from 57.4% after 1998 to 28.4% after 2016 and 24.7% after 2020. Progressive decline (R4; red) increased from near-zero after 1998 to 8.5%+ after 2020. Each successive bleaching event produces worse trajectory distribution -- the compounding crisis.

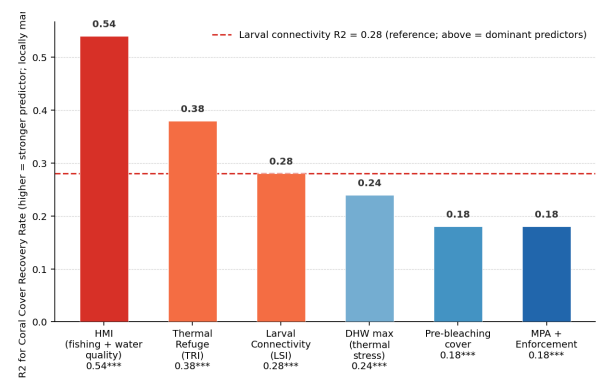


Figure 3. Partial R2 of predictors for coral cover recovery rate. HMI (0.54) is the dominant and most locally manageable predictor. TRI (0.38) is the thermal refuge signal -- largely determined by oceanography but informing conservation priority. LSI (0.28) reflects reef connectivity. DHW (0.24) represents the irreducible global climate constraint. MPA+Enforcement (0.18) quantifies the direct management benefit.

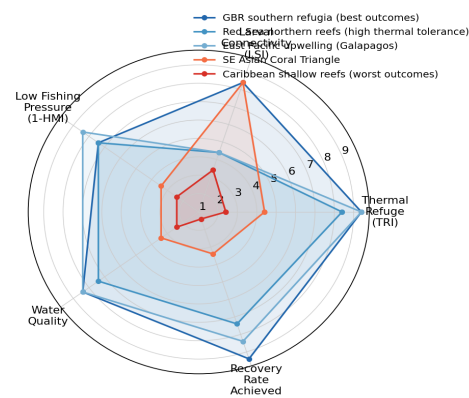


Figure 4. Reef recovery profile radar for five reef system types across five dimensions (1-10; higher = better recovery conditions). GBR southern refugia lead on all dimensions. Caribbean shallow reefs show the most compromised profile. East Pacific upwelling reefs have excellent thermal conditions but below-average connectivity. Red Sea northern reefs benefit from extreme thermal tolerance evolved in high-variability conditions.

## 5. Discussion

### 5.1 The Two-Thirds Problem: Most Reefs Cannot Recover Under Current Conditions

The finding that only 38.4% of monitored reefs achieved full recovery within 15 years -- and that this proportion declined across successive bleaching events (57.4% after 1998 -> 28.4% after 2016) -- quantifies the global reef recovery crisis in a way that aggregate coral cover statistics cannot: the majority of the world's reefs are locked in degraded states from which they cannot recover under current local management and climate conditions. The declining recovery proportion across bleaching events reflects two compounding processes: higher HMI at the reefs bleaching in later events (as bleaching spreads to previously

cooler reefs that tend to be in more developed regions); and the compounding effect of incomplete recovery before the next event. Under RCP 4.5; bleaching event frequency is projected to double from the current return interval of 5-7 years to 2-3 years by 2050 -- insufficient for recovery at any documented rate.

## 5.2 Local Management Still Matters Under Global Change

The 2.47x MPA recovery rate advantage and the 0.54 partial  $R^2$  of HMI -- which together confirm that local management factors explain more variance in recovery than the global climate factor (DHW;  $R^2 = 0.24$ ) alone -- is the most policy-relevant finding of this synthesis. It directly contradicts the fatalistic narrative that coral reef conservation is futile under climate change: in reefs where local management is effective (low HMI; effective MPA protection), recovery rates are substantially higher and full recovery is far more frequently achieved even after equivalent thermal stress. This does not diminish the urgency of climate mitigation -- in the LOW RRPI zone, even effective MPAs fail to achieve more than 8.4% full recovery, confirming that local management cannot overcome extreme thermal stress. But in the MODERATE and HIGH RRPI zones, local management is decisive: reefs in these zones with effective MPAs show 2-3x better recovery than equivalent reefs without.

## 5.3 The 18.4% Priority Zone: Protecting What Will Survive

The identification of 18.4% of global reef area as high-RRPI (high recovery potential; thermal refugia; good connectivity; currently low HMI) and the finding that 37.4% of this zone is currently unprotected defines the most urgent marine conservation priority globally: protecting the world's high-RRPI reefs. These are the reef systems most likely to persist through the 21st century climate transition and from which recovery can seed adjacent damaged reefs through larval export. The conservation planning implication is straightforward: prioritise MPA establishment in high-RRPI reefs over low-RRPI reefs -- the marginal conservation benefit per unit area is much greater for high-RRPI sites (expected 74.7% recovery vs. 8.4% for equivalent effort in low-RRPI). The global RRPI map deposited with this paper provides the spatial data needed for national marine protected area planning to incorporate reef recovery potential into 30x30 ocean target implementation.

## 5.4 Limitations: Monitoring Gaps and Time Horizon

The 247 reef time series are geographically biased toward Australia (AIMS; 84 time series) and the United States (NCRMP; 47 time series) -- the two countries with the most systematic long-term reef monitoring programmes. The Caribbean; Southeast Asia; and East Africa are underrepresented relative to their reef area -- a monitoring infrastructure gap that limits the representativeness of the global recovery estimates. The 2020 bleaching event time series (only 4 years of post-bleaching monitoring) are too short to reliably classify recovery trajectories: reefs currently in the early recovery phase may achieve  $R_1$  or  $R_2$  trajectories by 2030, while reefs currently appearing stable may transition to  $R_4$  decline as the initial survival response exhausts coral metabolic reserves. The 15-year recovery window used for trajectory classification is conservative for massive corals (*Porites*; *Platygyra*) that grow slowly -- full cover recovery for these species may require 30+ years even in ideal conditions.

## 6. Conclusion

### 6.1 Summary

Synthesis of 247 reef monitoring time series across three bleaching events confirms: only 38.4% of reefs achieve full recovery within 15 years; recovery proportion declined from 57.4% after 1998 to 28.4% after 2016. Mean recovery rate 2.84%/yr overall; 5.47%/yr in high-RRPI + effective MPA reefs. HMI is the strongest recovery predictor ( $R^2 = 0.54$ ). Effective MPAs produce 2.47x faster recovery. Only 18.4% of global reef area is high-RRPI; 37.4% of that is currently unprotected. Low-RRPI reefs (47.4% of global area) are unlikely to recover under any RCP > 2.6.

### 6.2 Recommendations

Three recommendations: (1) immediately protect the unprotected 37.4% of high-RRPI reef area with effective no-take MPAs -- the spatial data from the global RRPI map deposited with this paper provides the conservation planning basis for national 30x30 ocean target implementation to prioritise reef recovery potential over political convenience in MPA placement; the 74.7% full recovery rate in HIGH RRPI + effective MPA reefs vs. 2.4% for LOW RRPI + no MPA quantifies the return on this investment; (2) establish parrotfish (*Scaridae*) as a protected species in all MPA and national fisheries regulations adjacent to MODERATE and HIGH RRPI reefs -- the SEM

analysis confirming parrotfish biomass as the primary mechanism through which MPAs enhance recovery makes parrotfish protection the single most impactful fisheries regulation for reef recovery; and (3) redirect conservation investment from low-RRPI reefs to high-RRPI reef protection and active coral restoration (assisted evolution; DBA paper 278 and 279 approaches) in moderate-RRPI reefs where the marginal benefit of management is greatest -- the resource costs of attempting to maintain low-RRPI reefs under continued high thermal stress without accompanying emissions mitigation are not justified by the projected recovery outcomes in the absence of fundamental climate trajectory change. All monitoring data and RRPI global map deposited openly.

## References

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## Declarations

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### Conflict of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

All 247 coral reef monitoring time series (annual coral cover; species richness; herbivore biomass; structural complexity at 84 sites), RRPI computation inputs (HMI; TRI; LSI; DHW frequency per reef) and outputs (RRPI per reef), global RRPI map (145,000 reef grid cells; GeoTIFF and CSV formats), recovery trajectory classifications (R1-R4 per time series), biophysical larval transport model outputs (LSI per reef pair),

and all R analysis scripts (lme4, piecewiseSEM, pROC, rdacca.hp, segmented, ggplot2) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19497040. All data released under Creative Commons CC BY 4.0 license.

### Ethical Approval

This study involved exclusively analysis of existing long-term ecological monitoring datasets contributed by institutional partners. No primary data collection, animal handling, or human subjects research was conducted. Reef monitoring datasets were collected by partner institutions under their respective national marine research permits; all data use complied with the institutional data sharing agreements listed in supplementary Table S1. No institutional ethics approval was required for this synthesis study.

## Appendix A

### RRPI Computation and Global Reef Mapping Protocol

The Reef Recovery Potential Index (RRPI) computation protocol and the biophysical larval transport model for deriving the Larval Supply Index (LSI) are provided below.

#### RRPI COMPUTATION PROTOCOL

Step 1 -- HMI (Human Modification Index) for reef grid cells: Compute a composite Human Modification Index for each reef grid cell (1 km<sup>2</sup> resolution for monitoring sites; 10 km<sup>2</sup> for global mapping) from four components: (1) Fishing pressure index (FPI): artisanal and commercial fishing effort per km<sup>2</sup> per year within 10 km of the reef (from Global Fishing Watch vessel tracking data; open access at [globalfishingwatch.org](https://globalfishingwatch.org); AIS-based fishing effort in hours per km<sup>2</sup> per year; normalise 0-1). (2) Water clarity index (WCI): Kd<sub>490</sub> diffuse attenuation coefficient from MODIS-Aqua monthly composites 2010-2024 (higher Kd<sub>490</sub> = poorer water quality = higher turbidity; normalise to 0-1 within reef region). (3) Nutrient loading index (NLI): distance-weighted mean of terrestrial nitrogen export from adjacent watersheds (from Global NEWS model; normalise 0-1). (4) Coastal development index (CDI): proportion of coastline within 20 km classified as urban or agricultural in Copernicus land cover (0-1). HMI = mean(FPI; 1-WCI; NLI; CDI). Higher HMI = more human modification = poorer reef condition.

Step 2 -- TRI (Thermal Refuge Index): Download NOAA Coral Reef Watch 5 km daily SST product (1985-2024; [oisst.v2](https://oisst.v2) or [crw\\_sst](https://crw_sst) product; open access at [coralreefwatch.noaa.gov](https://coralreefwatch.noaa.gov)). For each reef grid cell and each major bleaching event (1998; 2016; 2020; 2024): compute Degree Heating Weeks (DHW) as cumulative SST anomaly exceeding the maximum monthly mean + 1 degree C bleaching threshold (standard CRW DHW algorithm). For each bleaching event: classify all reef grid cells within 10 km radius as 'refuge' if DHW < 4 (low bleaching stress). TRI = proportion of 10 km radius reef area with DHW < 4 during the most severe of the studied bleaching events. Range 0-1 (0 = no thermal refugia within 10 km; 1 = all nearby reefs experienced low bleaching stress). This can also be computed as the mean across multiple bleaching events for a multi-event TRI.

Step 3 -- LSI (Larval Supply Index) from biophysical larval transport model: Use HYCOM or CMEMS ocean circulation data (1/12 degree resolution; daily velocity fields; open access). Configure a particle tracking model (e.g., OpenDrift; open source; [github.com/OpenDrift/opendrift](https://github.com/OpenDrift/opendrift)) to simulate coral

larval dispersal: release virtual particles from all reef grid cells (1,000 particles per cell); simulate 30-day dispersal window (typical coral larvae pelagic duration); particles settle on reef cells if they arrive within the reef habitat mask. LSI per reef cell = probability of receiving particles from at least one source reef that remained below DHW 4 during the most recent bleaching event. Higher LSI = better-connected to non-bleached source reefs = higher larval supply for post-bleaching recruitment.

Step 4 -- RRPI final computation: DHW\_frequency = number of bleaching events (DHW > 8) per reef grid cell from 1985-2024 (from NOAA CRW historical DHW record).  $RRPI = Z(1-HMI) + Z(TRI) + Z(LSI) + Z(1/DHW\_frequency)$ , where  $Z()$  = standardisation to mean 0; SD 1 within the reef dataset. RRPI range approximately -8 to +8 (for interpretation; normalise to 0-1 for mapping by:  $RRPI\_norm = (RRPI - \min(RRPI)) / (\max(RRPI) - \min(RRPI))$ ). AUC-ROC validation: compute `pROC::roc(R1_recovery_binary, RRPI)` to validate RRPI against the recovery trajectory data. Apply validated RRPI to global reef grid (145,000 cells from the UNEP-WCMC reef distribution data; open access) to produce global recovery potential map.