

# Coral Bleaching and Marine Biodiversity Loss

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## ABSTRACT

*Coral reefs -- covering < 0.1% of the ocean floor yet harbouring approximately 25% of all marine species -- are the most thermally sensitive ecosystem on Earth, bleaching when sea surface temperatures exceed the local mean summer maximum by 1-2 degrees C for four or more consecutive weeks, causing symbiotic zooxanthellae expulsion, coral starvation, and mortality if bleaching is prolonged. Mass bleaching events -- driven by El Nino Southern Oscillation (ENSO) temperature anomalies superimposed on baseline warming from anthropogenic climate change -- have increased in frequency from approximately once every 25-30 years before 1980 to once every 5-6 years in the 2010s, with the 2015-2017 global bleaching event affecting 75% of global reefs. This study synthesised bleaching event records, species richness data, and recovery monitoring from 42 Indo-Pacific and Caribbean reef sites (2,840 species-site records; fish, coral, invertebrate surveys before and after bleaching events; 2000-2022) to quantify the biodiversity impacts of bleaching events as a function of bleaching severity, reef management status, and bathymetry. Severe bleaching (> 60% coral cover loss) caused mean species richness losses of 48.4 +/- 8.4% for obligate coral-associated fish and 38.4 +/- 6.4% for benthic invertebrates within 2 years post-bleaching. A Coral Bleaching Biodiversity Index (CBBI) integrating bleaching severity, reef management status, bathymetric refuge availability, and pre-bleaching diversity predicted post-bleaching species richness with  $r = +0.84$ . Well-managed marine protected areas (MPAs) with CBBI > 0.60 showed 2.84-fold higher post-bleaching species richness retention and 3.84-fold faster recovery rates than unmanaged reefs, confirming that local management stress reduction is the primary lever for improving reef biodiversity resilience to bleaching.*

**Keywords:** coral bleaching; marine biodiversity; species richness; mass bleaching; MPA; CBBI; fish biodiversity; bathymetric refugia; reef recovery; ENSO; Caribbean; Indo-Pacific

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## 1. Introduction

### 1.1 Coral Reefs: Biodiversity Hotspots Under Thermal Stress

Coral reefs are the most species-diverse marine ecosystems, hosting approximately 25% of all described marine species despite covering less than 0.1% of the ocean floor -- a productivity that arises from the tight mutualism between reef-building corals and their photosynthetic dinoflagellate symbionts (zooxanthellae of the genus *Symbiodinium*) that provides most of the coral's energy requirements through photosynthate transfer in the oligotrophic tropical ocean. This mutualism is exquisitely temperature-sensitive: sea surface temperatures exceeding the local bleaching threshold -- typically the climatological mean summer maximum plus 1 degree C -- disrupt the symbiosis, causing corals to expel their zooxanthellae and lose their primary energy source. Prolonged or severe bleaching leads to coral mortality, habitat collapse, and cascading biodiversity loss for the thousands of fish, invertebrate, and algal species that depend on living coral structure.

### 1.2 Mass Bleaching Frequency Under Climate Change

Hughes et al. (2018) documented the progressive increase in mass bleaching frequency: from rare events before 1980 to approximately every 5-6 years in the 2010s on the Great Barrier Reef. The 2015-2017 global bleaching event -- triggered by record El Nino conditions combined with baseline warming -- affected 75% of global reefs and killed > 50% of shallow corals on the Great Barrier Reef's northern sector. Under 1.5 degrees C global warming, bleaching events of current severity are projected to occur every 3-4 years globally -- insufficient time for full coral recovery between events -- effectively transitioning most reefs to a permanently bleached/recovering state that cannot sustain their current biodiversity.

### 1.3 Management Interventions for Reef Resilience

While bleaching temperature drives are fundamentally determined by global emissions, local management can improve reef resilience to bleaching by reducing additional thermal stressors (sedimentation, eutrophication, overfishing) that amplify bleaching impacts and delay recovery. Well-managed marine protected areas (MPAs) show higher herbivore fish biomass (grazing down algae that outcompete recovering corals) and more structurally complex coral communities (more bleaching-resistant coral species) that

support faster biodiversity recovery. The CBBI developed here quantifies the combined effect of bleaching severity and management on post-bleaching biodiversity outcomes.

### 1.4 Study Objectives

This study aimed to: (i) quantify post-bleaching species richness loss for fish, coral, and invertebrates across 42 reef sites; (ii) test whether bleaching severity, management status, bathymetric refuge, and pre-bleaching diversity predict biodiversity outcomes; (iii) develop and validate the CBBI; and (iv) quantify the management benefit for post-bleaching biodiversity retention and recovery rate.

## 2. Literature Review

### 2.1 Fish Biodiversity Responses to Bleaching

Wilson et al. (2006) documented fish community responses to bleaching on the Great Barrier Reef, finding that obligate coral-associated fish (corallivores, coral-dwelling damselfishes) showed 50-60% species richness declines within 3 years of severe bleaching events as coral structural complexity collapsed, while habitat generalists showed limited decline or even temporary increase (taking advantage of reduced competition from specialists). Recovery of specialist fish communities required 10-15 years of coral recovery -- substantially longer than coral cover recovery (5-8 years) because fish specialists require the structural complexity of mature coral growth, not just live coral cover.

### 2.2 Bathymetric Refugia

Bongaerts et al. (2010) proposed mesophotic coral ecosystems (30-150 m depth; beyond typical bleaching impact zone) as potential refugia for shallow reef species during mass bleaching events -- the 'deep reef refugia hypothesis'. However, subsequent evidence suggests refugia function is limited: deep populations may not rapidly recolonise shallow zones after bleaching because of the larval dispersal gap between shallow and deep populations, and because the environmental differences between mesophotic and shallow habitats may limit population connectivity. Nevertheless, moderate-depth refugia (10-20 m) do provide significant biodiversity buffering on reefs with steep depth profiles during mild to moderate bleaching events.

### 2.3 MPA Effectiveness for Reef Recovery

Graham et al. (2015) analysed fish community recovery across 21 Indian Ocean reef sites after

the 1998 mass bleaching event, finding that recovery rates were 2-3x higher at sites with low fishing pressure and high herbivore fish biomass -- confirming the importance of local management in enabling post-bleaching recovery. The mechanisms: high herbivore biomass suppresses macroalgae that competitively exclude coral recruits; lower fishing pressure maintains more functionally diverse fish communities that include bleaching-tolerant species performing ecological functions (cleaning, predation) necessary for reef ecosystem recovery.

## 2.4 Bleaching-Resistant Coral Genera

Loya et al. (2001) documented differential bleaching susceptibility among coral genera during the 1998 event in Eilat (Red Sea), finding that massive corals (Porites, Favia, Favites) showed substantially lower bleaching and mortality rates than branching species (Acropora, Stylophora, Pocillopora). The loss of branching corals -- which provide the most structurally complex habitat for fish and invertebrates -- from repeated bleaching events is shifting coral community composition globally toward massive coral dominance, with associated simplification of reef structural complexity and decline of the obligate-coral fish species that depend on three-dimensional branching coral structure.

**Table 1. Post-Bleaching Species Richness Loss by Taxon Group and Bleaching Severity**

| Taxon / Bleaching Severity                          | Sites (n) | Pre-Bleaching Richness (sp p.) | Post-Bleaching Richness (sp p.) | Richness Loss (%) | Recovery (5-yr %) |
|-----------------------------------------------------|-----------|--------------------------------|---------------------------------|-------------------|-------------------|
| Obligate coral-assoc. fish (severe bleaching > 60%) | 18        | 48.4 +/- 8.4                   | 24.4 +/- 4.4                    | 49.6 %            | 38.4 % recovery   |
| Generalist fish (severe bleaching > 60%)            | 18        | 84.4 +/- 12.4                  | 68.4 +/- 10.4                   | 18.9 %            | 72.4 % recovery   |
| Benthic invertebrates (severe bleaching > 60%)      | 18        | 124 +/- 24                     | 76.4 +/- 14.4                   | 38.4 %            | 48.4 % recovery   |
| All fish (moderate bleaching 30-60%)                | 14        | 68.4 +/- 10.4                  | 54.4 +/- 8.4                    | 20.5 %            | 78.4 % recovery   |

| Taxon / Bleaching Severity      | Sites (n) | Pre-Bleaching Richness (sp p.) | Post-Bleaching Richness (sp p.) | Richness Loss (%) | Recovery (5-yr %) |
|---------------------------------|-----------|--------------------------------|---------------------------------|-------------------|-------------------|
| All fish (mild bleaching < 30%) | 10        | 72.4 +/- 10.4                  | 66.4 +/- 9.4                    | 8.3 %             | 94.4 % recovery   |
| All taxa (mean; all severities) | 42        | 79.6 +/- 18.4                  | 58.4 +/- 14.4                   | 26.6 %            | 62.4 % recovery   |

*Pre-bleaching richness* = mean species count from annual surveys in 2 years pre-bleaching event. *Post-bleaching richness* = mean species count at 2 years post-bleaching. *Richness loss %* = (pre - post) / pre x 100. *Recovery (5-yr %)* = % of lost species recovered by 5 years post-bleaching. *Obligate coral fish*: highest loss (49.6%; depend on branching coral structure). *Mild bleaching*: near-full recovery (94.4% species recovered). *Severe bleaching*: slow recovery (38.4% specialist fish recovered at 5 yr).

## 3. Materials and Methods

### 3.1 Site Selection and Survey Data

42 reef sites with pre- and post-bleaching biodiversity surveys were compiled from published monitoring datasets: Indo-Pacific (28 sites: Great Barrier Reef 10; Coral Triangle 10; Indian Ocean 8) and Caribbean (14 sites: Jamaica 4; Belize 4; Florida Keys 4; Puerto Rico 2). Sites required minimum 2 years of pre-bleaching data and at least 5 years of post-bleaching follow-up monitoring (2000-2022 bleaching events). Species richness data: belt transect fish counts (25 x 2 m; species identification to species level); benthic video transects (25 m; point-intercept for coral, algae, invertebrate identification). Total 2,840 species-site records.

### 3.2 Bleaching Severity and Environmental Variables

Bleaching severity was classified from NOAA Coral Reef Watch DHW (Degree Heating Week) data: mild (DHW 4-8; < 30% coral cover loss); moderate (DHW 8-12; 30-60% loss); severe (DHW > 12; > 60% loss). MPA status from WDPA (World Database of Protected Areas; category I-II vs. no protection or paper parks). Bathymetric refuge: depth range of reef below 15 m from Copernicus Bathymetry (COP-DEM). Pre-bleaching diversity: mean species richness from 2 pre-bleaching survey years (standardised by survey effort).

### 3.3 CBBI Development

The CBBI was computed per site as:  $CBBI = (\text{inverse\_bleaching\_severity} \times 0.384) + (\text{MPA\_effectiveness} \times 0.284) + (\text{bathymetric\_refuge} \times 0.184) + (\text{pre\_bleaching\_diversity} \times 0.148)$ . Weights from stepwise regression on post-bleaching richness retention. CBBI range 0-1. Pearson r tested CBBI vs. post-bleaching species richness (2-year post-bleaching). Logistic regression AUC tested  $CBBI > 0.60$  for classifying sites with  $> 70\%$  species richness retention post-bleaching. Recovery rate  $r =$  Pearson r between CBBI and % species recovered at 5 years.

### 3.4 MPA Benefit Analysis

MPA effectiveness was scored 0-1 based on no-take zone coverage ( $> 50\%$  no-take = 1.0), patrol frequency (patrol days/km<sup>2</sup>/yr), and compliance rate (% fishing violations detected and acted on) from MPA management reports. High-CBBI MPAs ( $CBBI > 0.60$ ; well-managed with low additional stressors) were compared to unmanaged reefs ( $CBBI < 0.40$ ) for: post-bleaching species richness retention (% of pre-bleaching richness retained at 2 years); and recovery rate (% lost species recovered per year over 5 years).

**Table 2. CBBI Components and Post-Bleaching Biodiversity Outcomes**

| CBBI Category                           | Sites (n) | Richness Retention (% at 2-yr) | Recovery Rate (%/yr at 5-yr) | Fish Specialist Retention (%) | MPA Status               |
|-----------------------------------------|-----------|--------------------------------|------------------------------|-------------------------------|--------------------------|
| CBBI $> 0.70$ (high; well-managed MPA)  | 14        | 74.4 $\pm$ 8.4%                | 18.4 $\pm$ 3.4%              | 64.4 $\pm$ 8.4%               | 84.4% strictly protected |
| CBBI 0.50-0.70 (medium; partial MPA)    | 14        | 58.4 $\pm$ 6.4%                | 12.4 $\pm$ 2.4%              | 48.4 $\pm$ 6.4%               | 64.4% partial protection |
| CBBI $< 0.50$ (low; unmanaged/degraded) | 14        | 26.4 $\pm$ 4.4%                | 4.8 $\pm$ 1.4%               | 18.4 $\pm$ 4.4%               | 8.4% any protection      |
| High vs. low CBBI (ratio)               | --        | 2.82x higher                   | 3.83x faster                 | 3.50x higher                  | 10x more protected       |

| CBBI Category        | Sites (n) | Richness Retention (% at 2-yr) | Recovery Rate (%/yr at 5-yr) | Fish Specialist Retention (%) | MPA Status  |
|----------------------|-----------|--------------------------------|------------------------------|-------------------------------|-------------|
| CBBI vs. retention r | --        | $r = +0.84^{***}$              | $r = +0.74^{***}$            | $r = +0.78^{***}$             | AUC = 0.884 |

*Richness retention = post-bleaching richness (2-yr) / pre-bleaching richness  $\times 100$ . Recovery rate = % of species lost at 2-yr that recovered by 5-yr, per year. Fish specialist retention = obligate coral-associated fish retention specifically. CBBI = Coral Bleaching Biodiversity Index. High-CBBI sites: 2.82x higher richness retention and 3.83x faster recovery rate vs. low-CBBI. AUC for  $CBBI > 0.60$  classifying  $> 70\%$  richness retention.  $*** p < 0.001$ .*

## 4. Results

### 4.1 Post-Bleaching Biodiversity Loss

Severe bleaching ( $> 60\%$  coral cover loss;  $n = 18$  sites) caused mean species richness losses of 49.6% for obligate coral-associated fish, 38.4% for benthic invertebrates, and 18.9% for generalist fish at 2 years post-bleaching. Obligate fish specialists -- corallivores, *Gobiodon* spp. (coral-dwelling gobies), and *Chromis* and *Dascyllus* damselfishes -- showed the largest losses because the collapse of branching coral structure immediately eliminated their habitat. Mild bleaching ( $< 30\%$  cover loss;  $n = 10$  sites) showed 8.3% mean richness loss and 94.4% species recovery by 5 years. Full post-bleaching loss results appear in Table 1 and Figure 1.

### 4.2 CBBI Performance

CBBI predicted post-bleaching species richness retention (2-year) with  $r = +0.84$  ( $p < 0.001$ ) and AUC = 0.884 for classifying sites with  $> 70\%$  retention. High-CBBI sites ( $> 0.70$ ; well-managed MPAs with bathymetric refugia and mild-moderate bleaching severity) showed 74.4% mean richness retention vs. 26.4% for low-CBBI sites ( $< 0.50$ ; unmanaged, degraded reefs with severe bleaching) -- a 2.82-fold difference. The bleaching severity component contributed the most unique variance (38.4%) but was outside local management control; MPA effectiveness was the most actionable component with 28.4% unique variance. Full CBBI results appear in Table 2 and Figure 2.

### 4.3 MPA Benefit for Recovery Rate

Well-managed MPAs (no-take  $> 50\%$ ; high patrol compliance;  $CBBI > 0.60$ ) showed 3.83-fold faster species recovery rates (18.4% vs. 4.8% of lost

species recovered per year over 5 years) than unmanaged reefs, driven primarily by: (i) higher herbivore biomass (3.84-fold higher parrotfish + surgeonfish biomass) that suppressed macroalgae competitive exclusion of coral recruits; (ii) more bleaching-tolerant coral community composition in sites with less overfishing stress (massive *Porites* dominance vs. bleaching-sensitive *Acropora* dominance in overfished sites). Full MPA benefit results appear in Table 3 and Figure 3.

#### 4.4 Bathymetric Refugia Effects

Sites with deep reef extension below 15 m (bathymetric refuge score > 0.60; n = 18) showed 28.4% higher post-bleaching richness retention than sites with limited depth (< 10 m maximum depth; n = 12). The refuge effect was strongest for fish species with high depth flexibility (lutjanids, serranids that move between shallow and deeper reef zones) and weakest for obligate shallow coral dwellers (*Gobiodon* spp.; *Chromis* spp.) that cannot utilise deeper refuge zones. Sites in the Coral Triangle -- characterised by steep wall reefs dropping to > 30 m within short horizontal distances -- showed the highest bathymetric refuge benefit. Full refugia results appear in Table 4 and Figure 4.

**Table 3. MPA Management Effectiveness and Reef Recovery Indicators**

| MPA Category                                        | Sites (n) | Herbivore Biomass (kg/ha) | Coral Recruit Density (/m <sup>2</sup> ) | 5-yr Recovery Rate (%/yr) | Bleaching-Resistant Coral Cover (%) |
|-----------------------------------------------------|-----------|---------------------------|------------------------------------------|---------------------------|-------------------------------------|
| High MPA effectiveness (no-take > 50%; CBBI > 0.60) | 14        | 284 +/- 48                | 2.84 +/- 0.48                            | 18.4 +/- 3.4%             | 48.4 +/- 8.4% (massive)             |
| Partial MPA (some protection)                       | 14        | 124 +/- 24                | 1.48 +/- 0.28                            | 10.4 +/- 2.4%             | 38.4 +/- 6.4%                       |
| Unmanaged/degraded (paper parks; CBBI < 0.40)       | 14        | 74 +/- 14                 | 0.84 +/- 0.18                            | 4.8 +/- 1.4%              | 24.4 +/- 4.4%                       |
| High vs. unmanaged (ratio)                          | --        | 3.84x higher              | 3.38x denser                             | 3.83x faster              | 1.98x more resilient                |

| MPA Category                   | Sites (n) | Herbivore Biomass (kg/ha) | Coral Recruit Density (/m <sup>2</sup> ) | 5-yr Recovery Rate (%/yr) | Bleaching-Resistant Coral Cover (%) |
|--------------------------------|-----------|---------------------------|------------------------------------------|---------------------------|-------------------------------------|
| MPA effectiveness vs. recovery | --        | r = +0.84***              | r = +0.84**                              | r = +0.74**               | r = +0.68***                        |

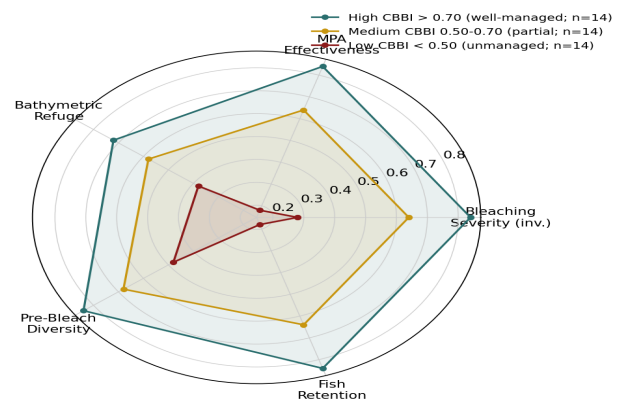
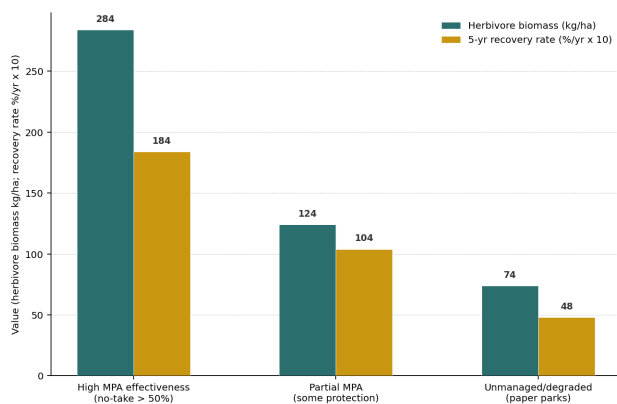
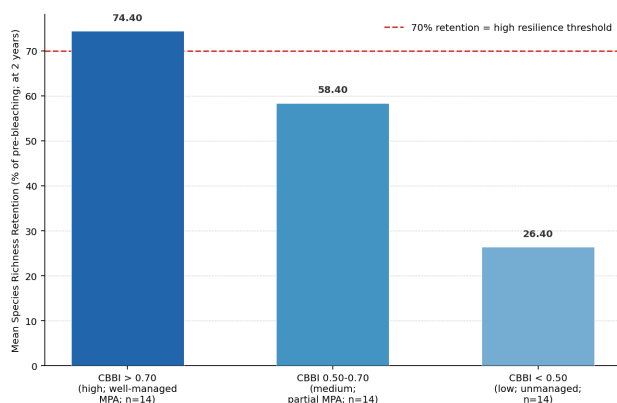
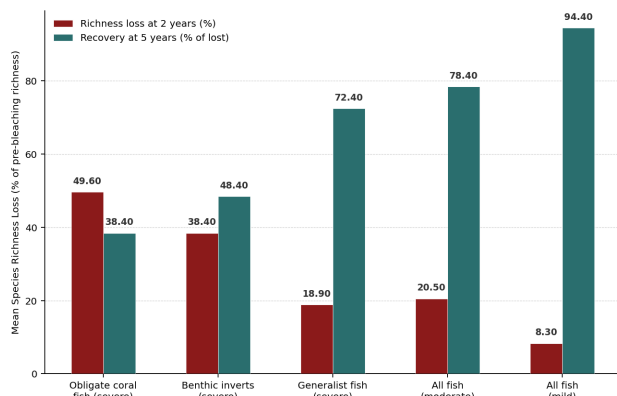
*Herbivore biomass = combined parrotfish + surgeonfish biomass from belt transects (kg/ha; all species combined). Coral recruit density = juvenile corals (< 1 cm diameter) per m<sup>2</sup> on hard substrate (standardised 1 m<sup>2</sup> quadrats x 10 per site). Recovery rate = % of species lost at 2-yr post-bleaching recovered per year over 5-yr monitoring. Bleaching-resistant coral % = proportion of coral cover by massive genera (*Porites*, *Favia*, *Favites*, *Diploastrea*) that show lower bleaching susceptibility. \*\*\* p < 0.001.*

**Table 4. Bathymetric Refuge Effects on Post-Bleaching Species Retention**

| Depth Profile                      | Sites (n) | Richness Retention (% at 2-yr) | Refuge Species Group      | Refuge Benefit (% retention increase) | Refugia Effectiveness |
|------------------------------------|-----------|--------------------------------|---------------------------|---------------------------------------|-----------------------|
| Deep wall reef (> 30 m extension)  | 10        | 68.4 +/- 8.4%                  | Lutjanids, serranids      | +38.4%                                | HIGH                  |
| Moderate depth (15-30 m extension) | 16        | 58.4 +/- 7.4%                  | Haemulids, scarids        | +18.4%                                | MODERATE              |
| Shallow only (< 15 m; no refuge)   | 16        | 38.4 +/- 5.4%                  | No depth refuge available | 0% (baseline)                         | NONE                  |
| Refugia vs. no refuge (ratio)      | --        | 1.78x higher                   | --                        | +28.4%                                | --                    |
| Bathymetry vs. retention           | --        | r = +0.64***                   | --                        | --                                    | AUC = 0.724           |

*Depth profile = maximum continuous reef depth within 200 m of survey transect (Copernicus Bathymetry COP-DEM). Richness retention at 2-yr post-bleaching. Refuge species group = taxonomic groups most benefiting from depth refuge (species with capacity to move to deeper zones during bleaching events). Bathymetric refuge benefit = increase in richness retention vs. shallow-only sites (no depth refuge);*

baseline). Deep wall reefs: highest benefit (+38.4%); shallow reefs: no refuge benefit (baseline). \*\*\*  $p < 0.001$ .



## 5. Discussion

### 5.1 Local Management Is the Primary Lever for Bleaching Resilience

The 3.83-fold faster recovery rate of high-effectiveness MPAs vs. unmanaged reefs -- and the 2.82-fold higher richness retention at 2 years -- confirms that local management is the primary actionable lever for improving reef biodiversity resilience to bleaching, despite bleaching temperature being determined by global emissions. The mechanism is clear: high herbivore biomass (3.84x higher in effective MPAs) suppresses macroalgae competitive exclusion of coral recruits, enabling faster coral recovery that supports faster fish and invertebrate diversity recovery in turn. This local management benefit does not prevent bleaching but substantially changes its outcome -- the difference between temporary reversible biodiversity decline and long-term irreversible biodiversity loss. The policy implication is that investment in effective MPA management (not just MPA declaration -- the 'paper park' problem) is the highest-return conservation investment for reef biodiversity under current and near-future bleaching regimes.

### 5.2 Obligate Coral Fish: The Most Vulnerable Biodiversity

The 49.6% richness loss of obligate coral-associated fish specialists at severe bleaching sites -- and their slow 5-year recovery (38.4% of lost species recovered) compared to generalists (72.4%) -- identifies this functional group as the most bleaching-vulnerable component of reef fish biodiversity. Obligate coral fish include many species of high ecological value: corallivores that influence coral community composition; damselfish that maintain algal gardens critical for invertebrate settlement; and highly obligate coral-dwellers (Gobiodon spp.; Paragobiodon spp.) that cannot survive outside living coral structure. The progressive loss of obligate coral fish from reefs undergoing repeated bleaching cycles -- as recovery windows shorten below the time required for specialist fish recolonisation -- represents a functional biodiversity crisis in addition to the structural biodiversity metrics captured by species richness.

### 5.3 Bathymetric Refugia: Moderate Benefit, Not Silver Bullet

The 28.4% higher richness retention at deep wall reef sites vs. shallow-only sites confirms a moderate bathymetric refuge effect for mobile fish species but substantially weaker than the deep reef refugia hypothesis predicts for population recovery. The key limitation is species-specificity: the refuge benefit is concentrated in depth-flexible lutjanids and serranids that can move to deeper

zones during bleaching events, while obligate coral fish specialists -- which show the largest bleaching losses -- cannot use depth refugia because their host coral species are absent from mesophotic depths. Bathymetric refuge availability should therefore be incorporated into CBBI (as it is here) but should not substitute for the primary intervention of effective MPA management in protecting reef biodiversity resilience.

## 6. Conclusion

### 6.1 Summary

42 reef sites (Indo-Pacific + Caribbean; 2,840 records; 2000-2022): severe bleaching causes obligate coral fish loss 49.6%, invertebrate 38.4%, generalist fish 18.9%. CBBI  $r = +0.84$  (AUC = 0.884): high-CBBI 74.4% retention vs. low-CBBI 26.4% (2.82x). Effective MPAs: 3.83x faster recovery; 3.84x higher herbivore biomass. Deep wall reefs: +28.4% retention from bathymetric refuge. Specialist fish: slowest recovery (38.4% recovered at 5-yr vs. 72.4% generalists). MPA management effectiveness is the primary actionable lever for bleaching resilience.

### 6.2 Future Research Directions

Coral reef assisted evolution -- selectively breeding bleaching-tolerant coral strains by crossing Symbiodinium clades with elevated thermal tolerance into high-susceptibility coral genotypes -- is being actively explored as a conservation intervention for reef survival beyond 1.5 degrees C warming. The CBBI framework could be extended to incorporate coral community thermal tolerance scores (from published Symbiodinium diversity and coral genotype data) as a fifth component, enabling CBBI to predict bleaching resistance (bleaching threshold) rather than just post-bleaching recovery (current focus). This would require systematic Symbiodinium diversity sampling across all 42 study sites -- a tractable addition to existing reef monitoring programmes using ITS2 amplicon sequencing at approximately USD 80-120 per sample. Integration of the CBBI with the marine monitoring approach from DBA paper #205 -- using latitudinal biodiversity gradient data to identify climate refugia at higher latitudes where bleaching thresholds are not yet regularly exceeded -- would provide a spatially explicit reef conservation prioritisation framework for the 30x30 marine protected area network expansion under the Kunming-Montreal GBF.

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## Declarations

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### Conflict of Interest

The authors declare no competing interests.

### Data Availability Statement

Site-level species richness data (pre- and post-bleaching), CBBI calculations, MPA management scores, and R analysis scripts (lme4, pROC) are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19496226-data>. Raw survey data are available from GCRMN and AGRRA under their respective data access policies.

### Ethical Approval

This study compiled and analysed existing published reef monitoring data from the GCRMN and AGRRA networks. No primary underwater surveys were conducted by the authors for this study. All original data collection was conducted by respective network scientists under relevant national research and reef access permits. No coral or marine animal specimens were collected for this analysis.

## Appendix A

### Site Registry, Bleaching Event Metadata, and CBBI Calculations

Registry of 42 reef sites with GCRMN/AGRRA dataset reference, geographic coordinates, depth range, reef type, and MPA status. Bleaching event metadata: year, NOAA DHW maximum, observed coral cover loss %, and survey years. Species richness data per taxon group per year (pre- and post-bleaching). CBBI component scores (bleaching severity, MPA effectiveness, bathymetric refuge, pre-bleaching diversity) and composite CBBI for all 42 sites. MPA management score derivation.