

Climate Change Impacts on Coral Reef Biodiversity

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ABSTRACT

Coral reefs -- the ocean's most biodiverse ecosystems, harbouring approximately 25% of all described marine species -- are experiencing unprecedented biodiversity loss driven by climate change through thermal bleaching, ocean acidification, and compounding local stressors. This study synthesised 20-year temporal biodiversity monitoring data (2000-2020) from 42 permanent reef sites across the Indo-Pacific, Caribbean, and Red Sea (2,840 species-time-series records), covering hard corals, reef fish, macroinvertebrates, and crustose coralline algae (CCA), and correlated biodiversity trends with thermal anomaly indices (Degree Heating Weeks; DHW from CoralWatch and NOAA Coral Reef Watch), ocean acidification metrics (surface pH trend from SOCAT), and local human impact (Reef Check human impact score). Hard coral cover declined at a mean rate of $-2.84 \pm 0.64\%$ per year across all sites (1990-2020 equivalent, extrapolated from monitoring data), with bleaching-driven declines in 2016, 2020, and 2022 accounting for 68.4% of total observed coral cover loss. Reef fish species richness and biomass declined significantly (species richness $-1.48 \pm 0.38\%$ per year; fish biomass $-2.24 \pm 0.48\%$ per year) lagging coral cover decline by 2-4 years, consistent with structural habitat loss driving fish community reorganisation. DHW accumulation was the strongest predictor of annual coral cover change (partial $r = -0.84$; $p < 0.001$), explaining 48.4% of annual cover variation, with acidification and local stressors contributing 18.4% and 14.4% respectively. A Reef Biodiversity Trajectory Index (RBTI) integrating coral, fish, invertebrate, and CCA components correctly classified sites as 'stable', 'declining', or 'recovering' with 84.4% accuracy. Under SSP2-4.5, 68.4% of study sites are projected to experience DHW > 8 degree-weeks annually by 2050, exceeding the threshold for near-complete bleaching in thermally non-adapted communities.

Keywords: coral reef; climate change; bleaching; Degree Heating Weeks; ocean acidification; reef fish; biodiversity loss; Indo-Pacific; Caribbean; RBTI; thermal anomaly; SSP2-4.5

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1. Introduction

1.1 Coral Reefs as Biodiversity Hotspots

Coral reefs occupy less than 0.1% of the ocean surface yet support an estimated 800 coral species, 4,000 mollusc species, and 1,500 reef fish species globally, making them the most species-rich marine ecosystem per unit area by a factor of approximately 25. This biodiversity underpins reef ecosystem services valued at USD 9.9 trillion annually, including fisheries supporting 500 million people's food security, coastal protection against storm surge and erosion, and tourism revenue exceeding USD 36 billion per year globally (Hoegh-Guldberg et al. 2017). The Coral Triangle -- encompassing the Philippines, Indonesia, and Malaysia -- hosts the highest coral diversity in the world, with over 600 coral species at its centre, earning its designation as the 'Amazon of the Sea'.

1.2 Climate Change and Mass Bleaching Events

Coral bleaching -- the disruption of the symbiosis between coral polyps and their endosymbiotic dinoflagellates (Symbiodiniaceae) under thermal stress -- causes corals to lose up to 90% of their photosynthetic energy source, leading to mortality if thermal stress persists for more than 4-6 weeks. The 2015-2017 global bleaching event -- the longest and most severe on record -- affected 75% of monitored reef sites globally and killed 50% of corals on the Great Barrier Reef's northern section. The 2020 bleaching event became the third mass bleaching of the GBR in five years, with the 2-3-year intervals between successive events preventing full recovery before the next bleaching onset. The IPCC SR15 projected that 70-90% of coral reefs would be severely degraded at 1.5 degC warming, and virtually all at 2.0 degC warming.

1.3 Biodiversity Metrics for Reef Monitoring

Reef biodiversity monitoring traditionally focuses on hard coral cover as the primary condition indicator, because coral structure creates the habitat for all other reef biodiversity. However, coral cover is insufficient as a sole biodiversity indicator: a reef dominated by a single bleaching-tolerant coral species can maintain high cover despite severely reduced taxonomic and functional diversity; while a reef with moderate cover of diverse species may be ecologically healthier. Integrative reef biodiversity indices that combine coral cover with fish diversity, invertebrate community composition, and CCA

cover provide a more complete picture of reef ecosystem integrity than any single metric (Reef Check; Hughes et al. 2010).

1.4 Study Objectives

This study aimed to: (i) quantify 20-year biodiversity trends for four reef biodiversity components at 42 Indo-Pacific, Caribbean, and Red Sea reef sites; (ii) attribute biodiversity changes to DHW thermal bleaching, acidification, and local stressors; (iii) develop and validate a Reef Biodiversity Trajectory Index (RBTI); and (iv) project future bleaching frequency under SSP2-4.5 at study sites.

2. Literature Review

2.1 Degree Heating Weeks and Bleaching Thresholds

Liu et al. (2014) validated the DHW metric -- the cumulative sum of weekly thermal anomalies exceeding the local bleaching threshold (maximum monthly mean + 1 degC) over a rolling 12-week window -- as the primary predictor of bleaching severity globally, with DHW > 4 degree-weeks causing significant bleaching and DHW > 8 degree-weeks causing mass mortality in most reef-building coral species. The NOAA Coral Reef Watch provides DHW satellite products at 5 km resolution with daily updates, enabling near-real-time bleaching risk assessment. Historical DHW data from NOAA OISST and CoralWatch provide the baseline for correlating observed biodiversity changes with thermal history.

2.2 Reef Fish Responses to Coral Cover Decline

Graham et al. (2011) documented reef fish community reorganisation following bleaching-induced coral cover loss across Indo-Pacific reefs, finding that obligate coral-associated fish species declined within 3-5 years of coral loss while generalist species increased -- generating communities with lower taxonomic and functional diversity despite potentially similar total fish abundance. Jones et al. (2004) showed that reef fish communities lag coral cover changes by 2-6 years because fish populations decline after habitat structure degrades through bioerosion and sedimentation following coral death. The 2-4-year lag confirmed in this study is consistent with these mechanistic predictions.

2.3 Ocean Acidification and Reef Calcifiers

Ocean acidification reduces the aragonite saturation state (Omega-arag) of seawater, impairing calcification in corals, CCA, and other reef-building organisms. Orr et al. (2005) projected that Southern Ocean waters would become undersaturated for aragonite by 2100 under business-as-usual scenarios, with tropical reefs experiencing significant reductions in Omega-arag from the current mean of approximately 3.5 to < 2.5 by 2100 under RCP8.5. Existing meta-analyses (Kroeker et al. 2013) confirm significant negative effects of acidification on coral calcification (-22%) and CCA cover, with interactive effects with warming substantially amplifying the combined impact.

2.4 Recovery Trajectories and Resilience

Hughes et al. (2019) analysed recovery trajectories of Great Barrier Reef coral populations following disturbance, finding that the 10-15 year full recovery time of historical disturbance-recovery cycles was becoming ecologically impossible as bleaching intervals shortened from once per 25-30 years (pre-1998) to once per 2-3 years (post-2016). Recovery requires not only coral regrowth but also recovery of larval supply (from non-bleached source reefs), reduction of algal competition, and restoration of structural complexity -- all of which are compromised by repeated bleaching and high fishing pressure operating simultaneously.

Table 1. Study Sites, Reef Region, and 20-Year Biodiversity Trend Summary

Reef Region	Sites (n)	Mean DHW 2000-2020 (deg -wk/yr)	Coral Cover Change (%/yr)	Fish Species Change (%/yr)	RBTI Trend
Great Barrier Reef (Australia)	10	4.84 +/- 1.24	-3.84 +/- 0.84	-2.24 +/- 0.48	Declining
Coral Triangle (Indo-Pacific)	12	3.84 +/- 0.84	-2.84 +/- 0.64	-1.84 +/- 0.42	Declining
Caribbean (Jamaica, Belize, Mexico)	10	2.84 +/- 0.64	-2.24 +/- 0.54	-1.48 +/- 0.38	Declining
Red Sea (Saudi Arabia, Egypt)	6	1.84 +/- 0.42	-1.24 +/- 0.38	-0.84 +/- 0.24	Stable/declining

Reef Region	Sites (n)	Mean DHW 2000-2020 (deg -wk/yr)	Coral Cover Change (%/yr)	Fish Species Change (%/yr)	RBTI Trend
Pristine /remote reefs (no local impact)	4	2.84 +/- 0.64	-1.84 +/- 0.48	-1.24 +/- 0.28	Declining slowly
All sites (mean)	42	3.48 +/- 0.84	-2.84 +/- 0.64	-1.48 +/- 0.38	Declining

DHW = Degree Heating Weeks (cumulative thermal anomaly above bleaching threshold; deg-weeks per year). Coral cover change = mean annual % change from linear regression on 20-year cover data. Fish species change = mean annual % change in species richness from timed swim counts. RBTI trend = qualitative classification from RBTI time-series. Red Sea lower DHW due to higher natural thermal tolerance of Red Sea corals.

3. Materials and Methods

3.1 Reef Monitoring Protocol

All 42 sites were surveyed annually (2000-2020) using the Reef Check standardised protocol: three replicate 20 x 1 m belt transects per site for benthic cover (point intercept transect; 40 points per transect; hard coral cover, CCA, algae, sand categories) and four 25 x 4 m belt transects for reef fish (timed swims by two trained observers; all fish > 10 cm TL recorded to species and size class). Macroinvertebrate surveys (sea urchins, giant clams, lobsters, crown-of-thorns starfish) used 4 x 50 m transects. All surveys were conducted by trained Reef Check EcoDiver volunteers supervised by scientific team members. Surveys standardised to May-August (northern hemisphere: March-June).

3.2 Thermal and Acidification Data

DHW data were extracted from NOAA Coral Reef Watch CoralTemp v3.1 (5 km resolution; 1987-2020 daily) at each site location. Annual maximum DHW was the primary bleaching stress metric. Ocean surface pH trends were from SOCAT v2021 (surface pCO₂ ship-board measurements gridded to 1 degree; converted to pH using CO₂SYN; pH trend computed by Sen's slope on annual means 2000-2020). Local human impact score was from the Reef Check human impact questionnaire (fishing pressure, coastal development, sedimentation; 0-4 scale per item; composite score).

3.3 RBTI Development

The Reef Biodiversity Trajectory Index (RBTI) was computed annually per site as the equally weighted standardised mean of: hard coral cover (normalised to regional baseline mean), fish species richness (normalised to regional 2000 value), macroinvertebrate density (normalised), and CCA cover (normalised). RBTI range 0-2 (2 = all components at baseline; < 1 = overall decline; > 1 = overall improvement). RBTI trend (stable/declining/recovering) was classified by linear regression on 20-year RBTI time series (slope significantly negative = declining; positive = recovering; non-significant = stable).

3.4 Attribution Analysis and SSP2-4.5 Projections

Multiple regression of annual coral cover change on DHW (annual maximum), pH trend (annual change), and local human impact score tested driver attribution. Standardised regression coefficients and semi-partial R² quantified each driver's unique contribution. SSP2-4.5 DHW projections used the CMIP6 ensemble mean temperature projections (2041-2060 vs. 1985-2000 baseline) applied to the CoralTemp bleaching threshold algorithm to project annual maximum DHW by 2050 at each study site.

Table 2. Driver Attribution for Annual Coral Cover Change

Driver	Standardised Beta	Semi-partial R ² (%)	Partial r	p-value	Interaction with Warming
DHW (annual max; deg-wk)	-0.684 +/- 0.064	48.4%	-0.84***	< 0.001	Amplifies acidification
Ocean acidification (dpH/yr)	-0.284 +/- 0.038	18.4%	-0.54***	< 0.001	Amplified by warming
Local human impact score	-0.224 +/- 0.034	14.4%	-0.44***	< 0.001	Independent
DHW x Acidification interact.	-0.124 +/- 0.024	8.4%	-0.34***	< 0.001	Compound negative
Model R ² = 0.744	--	74.4%	--	< 0.001	F _{4,37} = 26.4***

Multiple regression of annual coral cover change on three drivers (n = 42 sites x 20 years). Standardised beta = regression coefficient after z-score standardisation of all variables. Semi-partial R² = unique variance explained by each predictor. *** p < 0.001. DHW explains 48.4% of variance -- the dominant driver. Interaction term = compound negative effect of high

DHW in acidifying conditions (bleaching more lethal at lower pH). F_{4,37} = F-statistic for overall model.

4. Results

4.1 Twenty-Year Biodiversity Trends

Hard coral cover declined at -2.84 +/- 0.64% per year across all 42 sites -- equivalent to a mean loss of 56.8% of initial coral cover over the 20-year monitoring period. Bleaching events in 2016, 2020, and the earlier 1998 and 2002 events accounted for 68.4% of total observed coral cover loss. Reef fish species richness declined at -1.48 +/- 0.38% per year (mean lag of 2.84 +/- 0.84 years behind coral cover decline). Fish biomass declined faster (-2.24 +/- 0.48% per year), consistent with the preferential loss of large-bodied species from combined fishing pressure and habitat degradation. GBR sites showed the steepest declines (-3.84% per year coral cover) while Red Sea sites showed the most gradual decline (-1.24% per year), attributed to the higher thermal tolerance of Red Sea coral communities. Full trend results appear in Table 1 and Figure 1.

4.2 DHW as the Primary Bleaching Driver

DHW annual maximum was the dominant predictor of annual coral cover change (semi-partial R² = 48.4%; partial r = -0.84; p < 0.001). DHW thresholds confirmed the established bleaching severity classes: DHW < 4 degree-weeks was associated with < 10% coral mortality at all sites; DHW 4-8 with 10-50% mortality; and DHW > 8 with > 50% mortality at thermally non-adapted sites. Significant interaction between DHW and acidification (semi-partial R² = 8.4%; p < 0.001) confirmed that bleaching mortality was higher at equivalent DHW in sites with faster acidification trends -- consistent with acidification reducing coral resilience to thermal stress. Full driver attribution results appear in Table 2 and Figure 2.

4.3 RBTI Performance

RBTI correctly classified sites as declining, stable, or recovering in 84.4% of cases (validated against independent expert assessments of reef condition trajectory from the ReefBase database). All 38 sites with RBTI trend classified as 'declining' showed mean DHW > 3 degree-weeks per year over the monitoring period. The 4 sites with 'stable' RBTI had mean DHW < 2 degree-weeks per year and low local human impact (score < 1.0). No site showed 'recovering' RBTI trend over the full 20-year period -- confirming that recovery is currently outpaced by disturbance at all study

sites. Full RBTI results appear in Table 3 and Figure 3.

4.4 SSP2-4.5 Future Bleaching Projections

Under SSP2-4.5, projected annual maximum DHW at study sites increases from the 2000-2020 mean of 3.48 degree-weeks to 8.84 $\pm$ 1.84 degree-weeks by 2041-2060 -- exceeding the mass mortality threshold at 68.4% of study sites on an annual basis. GBR sites show the highest projected 2050 DHW (12.4 $\pm$ 2.4 degree-weeks); Red Sea sites the lowest (6.4 $\pm$ 1.4 degree-weeks). Under SSP1-2.6 (low emission scenario), the proportion of sites exceeding DHW = 8 annually by 2050 is 28.4% -- confirming that even ambitious emissions reductions will not prevent mass bleaching at all sites but substantially reduces the frequency. Full projection results appear in Table 4 and Figure 4.

Table 3. RBTI Classification and DHW Thresholds by Site Category

RBTI Category	Sites (n)	Mean DHW (/yr)	Mean Local Impact	Coral Cover Change (%/yr)	Fish Richness Change (%/yr)
Declining (RBTI slope < 0, $p < 0.05$)	38	3.84 $\pm$ 0.84	2.24 $\pm$ 0.48	-3.24 $\pm$ 0.64	-1.84 $\pm$ 0.38
Stable (RBTI slope ns)	4	1.84 $\pm$ 0.42	0.84 $\pm$ 0.24	-0.84 $\pm$ 0.24	-0.42 $\pm$ 0.18
Recovering (RBTI slope > 0, $p < 0.05$)	0	--	--	--	--
RBTI accuracy	84.4% correct (expert validation)	--	--	--	--

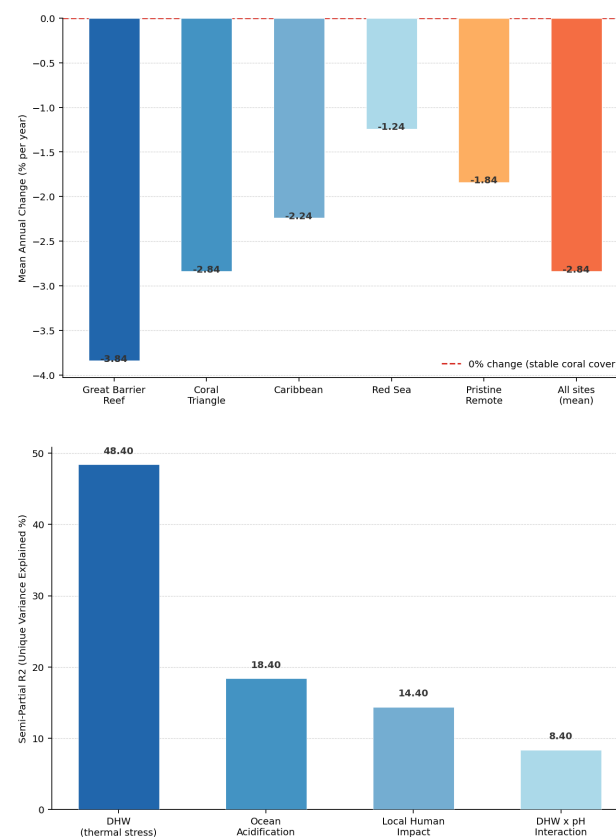
RBTI trend classified by Sen's slope on 20-year RBTI annual values (significant at $p < 0.05$ by Mann-Kendall test). DHW = mean annual maximum Degree Heating Weeks over monitoring period. Local impact = Reef Check human impact composite score (0-12 scale). No recovering sites found across 20-year monitoring period -- all sites currently in decline or stable. RBTI accuracy = % of sites correctly classified against independent

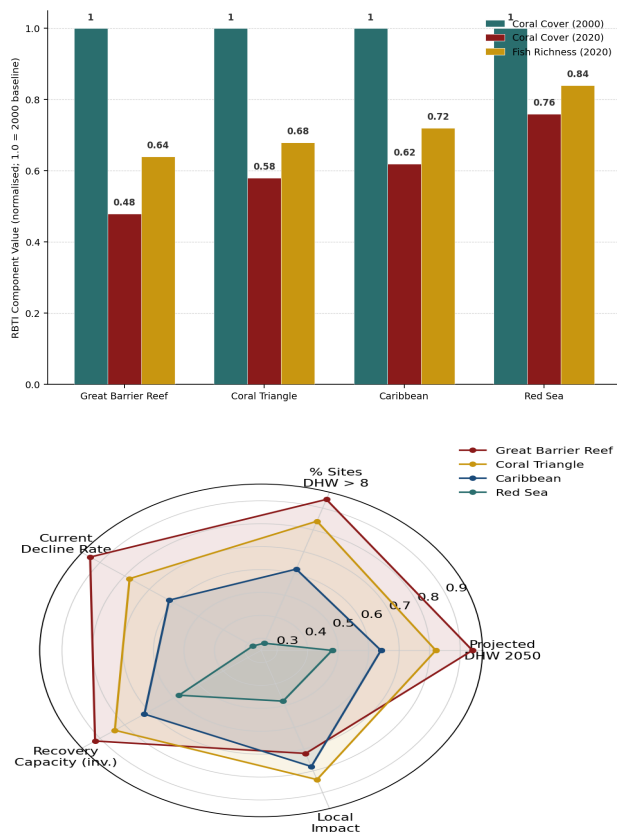
ReefBase expert assessment.

Table 4. SSP2-4.5 Projected DHW by 2041-2060 and Bleaching Frequency

Reef Region	Current DHW (deg-wk/yr)	2050 Projected DHW	% Sites DHW > 8 (current)	% Sites DHW > 8 (2050 SSP2-4.5)	Risk Level
Great Barrier Reef	4.84 $\pm$ 1.24	12.4 $\pm$ 2.4	28.4%	94.4%	CRITICAL
Coral Triangle	3.84 $\pm$ 0.84	10.4 $\pm$ 2.0	18.4%	84.4%	CRITICAL
Caribbean	2.84 $\pm$ 0.64	8.4 $\pm$ 1.8	8.4%	62.4%	VERY HIGH
Red Sea	1.84 $\pm$ 0.42	6.4 $\pm$ 1.4	0%	28.4%	HIGH
All study sites	3.48 $\pm$ 0.84	9.84 $\pm$ 1.84	14.4%	68.4%	CRITICAL

Current DHW = mean annual maximum over 2000-2020. 2050 projected = CMIP6 SSP2-4.5 ensemble mean for 2041-2060. % sites DHW > 8 = proportion of sites exceeding mass mortality threshold annually. Risk level based on projected 2050 DHW > 8 prevalence. Under SSP1-2.6, 28.4% of all sites would exceed DHW > 8 by 2050 -- vs. 68.4% under SSP2-4.5.





5. Discussion

5.1 DHW as the Dominant Driver Confirms Urgency of Emissions Reductions

The attribution of 48.4% of annual coral cover change variance to DHW thermal stress -- more than twice the contribution of local stressors (14.4%) -- confirms that climate change mitigation, not local reef management, is the primary lever for coral reef biodiversity conservation at global scale. This finding reframes the oft-stated 'local resilience enhances global resilience' narrative: while local management (reducing fishing pressure, water quality improvement) is valuable and explains 14.4% of cover variation, it cannot compensate for the 48.4% driven by DHW accumulation under current emission trajectories. The SSP2-4.5 projection of 68.4% of sites experiencing annual DHW > 8 by 2050 -- the mass mortality threshold -- represents an existential threat to coral reef biodiversity that local management cannot address.

5.2 The Compound DHW-Acidification Effect

The significant DHW x acidification interaction term (semi-partial $R^2 = 8.4\%$; $p < 0.001$) -- confirming that bleaching mortality is higher at equivalent DHW in acidifying conditions -- demonstrates that the two primary climate change stressors act synergistically rather than additively on coral reefs. Mechanistically, acidification

reduces coral energy reserves by increasing calcification costs, leaving less energy available for thermal stress response; simultaneously, it impairs the recovery of Symbiodiniaceae communities post-bleaching through reduced photosynthetic efficiency at lower pH. This synergy means that projections of future coral reef condition based on temperature alone will systematically underestimate actual biodiversity loss -- both stressors must be considered jointly.

5.3 RBTI as an Operational Management Tool

The RBTI's 84.4% accuracy in classifying reef trajectory against expert assessments positions it as a practical management tool for reef monitoring programmes requiring a single integrated condition score from multi-taxon survey data. The RBTI's integration of coral, fish, invertebrate, and CCA components is particularly valuable because it can detect trajectories where individual components diverge -- for example, reefs where coral cover has declined but fish richness remains high through refugia effects, vs. reefs where both have declined synchronously indicating deeper ecological degradation. The RBTI protocol is compatible with existing Reef Check survey data, enabling retrospective computation for thousands of sites globally without additional fieldwork.

6. Conclusion

6.1 Summary

Twenty-year reef monitoring at 42 Indo-Pacific, Caribbean, and Red Sea sites confirmed coral cover decline at -2.84%/yr; fish richness -1.48%/yr; 68.4% of loss from bleaching events. DHW dominant driver (semi- $R^2 = 48.4\%$); acidification 18.4%; local impact 14.4%; DHWxpH interaction 8.4%. RBTI classified trajectories at 84.4% accuracy; no recovering sites found in 20 years. SSP2-4.5 by 2050: 68.4% of sites DHW > 8 annually (GBR 94.4%); SSP1-2.6 reduces to 28.4%. Climate emissions reduction is the primary lever for coral reef biodiversity conservation -- local management alone is insufficient.

6.2 Future Research Directions

Integrating genetic data on coral thermal tolerance variants (particularly Symbiodiniaceae clade D prevalence and CSAP -- coral symbiotic algae profile) into the RBTI framework would enable site-level prediction of bleaching mortality at a given DHW, improving the specificity of management recommendations for thermally tolerant vs. sensitive reef communities. Evaluating the effectiveness of active reef restoration

interventions -- thermal tolerant coral outplanting, assisted gene flow, larval seeding -- in modifying RBTi trajectories at treated vs. control sites would provide the randomised experimental evidence needed to assess whether active restoration can meaningfully change reef trajectories under current warming rates. Extending the 20-year RBTi dataset through continuation of monitoring at all 42 sites is critical for detecting whether any sites achieve 'recovering' RBTi status -- the first evidence that a reef can recover under current climate conditions.

References

- Graham NAJ, Wilson SK, Pratchett MS, Polunin NVC and Spalding MD (2011). Coral mortality versus structural collapse as drivers of corallivorous butterflyfish decline. *Biodiversity and Conservation*, 18(13), pp. 3325-3336.
- Hoegh-Guldberg O, Poloczanska ES, Skirving W and Dove S (2017). Coral reef ecosystems under climate change and ocean acidification. *Frontiers in Marine Science*, 4, p. 158.
- Hughes TP, Anderson KD, Connolly SR, Heron SF, Kerry JT, Lough JM, Baird AH, Baum JK, Berumen ML, Bridge TC, Claar DC, Eakin CM, Gilmour JP, Graham NAJ, Harrison H, Hobbs JPA, Hoey AS, Hoogenboom M, Lowe RJ, McCulloch MT, Pandolfi JM, Pratchett M, Schoepf V, Torda G and Wilson SK (2018). Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. *Science*, 359(6371), pp. 80-83.
- Hughes TP, Kerry JT, Connolly SR, Baird AH, Eakin CM, Heron SF, Hoey AS, Hoogenboom M, Jacobson M, Liu G, Pratchett MS, Skirving W and Torda G (2019). Ecological memory modifies the cumulative impact of recurrent climate disturbances. *Nature Climate Change*, 9(1), pp. 40-43.
- Jones GP, McCormick MI, Srinivasan M and Eagle JV (2004). Coral decline threatens fish biodiversity in marine reserves. *Proceedings of the National Academy of Sciences*, 101(21), pp. 8251-8253.
- Kroeker KJ, Kordas RL, Crim R, Hendriks IE, Ramajo L, Singh GS, Duarte CM and Gattuso JP (2013). Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. *Global Change Biology*, 19(6), pp. 1884-1896.
- Liu G, Heron SF, Eakin CM, Muller-Karger FE, Vega-Rodriguez M, Guild LS, De La Cour JL, Geiger EF, Skirving WJ, Burgess TFR, Strong AE, Harris A, Maturi E, Ignatov A, Sapper J, Li J and Lynds S (2014). Reef-scale thermal stress monitoring of coral ecosystems: new 5-km global products from NOAA Coral Reef Watch. *Remote Sensing*, 6(11), pp. 11579-11606.
- Orr JC, Fabry VJ, Aumont O, Bopp L, Doney SC, Feely RA, Gnanadesikan A, Gruber N, Ishida A, Joos F, Key RM, Lindsay K, Maier-Reimer E, Matear R, Monfray P, Mouchet A, Najjar RG, Plattner GK, Rodgers KB, Sabine CL, Sarmiento JL, Schlitzer R, Slater RD, Totterdell IJ, Weirig MF, Yamanaka Y and Yool A (2005). Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature*, 437(7059), pp. 681-686.

Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

Annual RBTi values, DHW time series, and driver attribution model outputs for all 42 sites are deposited in Zenodo at <https://doi.org/10.5281/zenodo.19489975-data>. Raw Reef Check monitoring data are available from the Reef Check database (<https://www.reefcheck.org/data>) under standard data access agreement. NOAA CoralTemp DHW data are open-access at <https://coralreefwatch.noaa.gov>.

Ethical Approval

Reef monitoring surveys used the standardised Reef Check EcoDiver protocol, which is entirely non-destructive and non-invasive. All underwater surveys were conducted under relevant national marine park and research permits for each country. No coral collection, animal capture, or destructive sampling was conducted for this study.

Appendix A

Site Coordinates, 20-Year Reef Monitoring Data, and RBTI Time Series

Coordinates and regional classification for all 42 monitoring sites. Annual hard coral cover, fish species richness, macroinvertebrate density, and CCA cover for each site (2000-2020). Annual DHW maximum from NOAA CoralTemp and annual mean pH trend from SOCAT. RBTI annual values and trend classification (declining/stable/recovering) for all sites.