International Journal of Animal Biodiversity, Conservation and Systematics (IJABC)
ISSN: 3117-6925
https://stanfordgroup.org/index.php/IJABC/issue/archive

Anthropocene Effects on Marine Biodiversity

Daniel Jensen[1], Nina Petrov[2], Lea Novak[3]

[1] Associate Professor, Department of Computer Science, Nordic Technical University, Stockholm, Sweden. Email: daniel.jensen522@yahoo.com | ORCID: 9730-6646-8584-9752
[2] Professor, Institute of Intelligent Systems, Mediterranean Institute of Technology, Rome, Italy. Email: nina.petrov893@yahoo.com | ORCID: 5734-1261-4808-2257
[3] Research Scientist, Department of Artificial Intelligence, Central European Tech University, Vienna, Austria. Email: lea.novak737@yahoo.com | ORCID: 4825-5509-1209-5636

ABSTRACT

The Anthropocene epoch is characterised by an unprecedented acceleration of anthropogenic pressures on marine ecosystems, including ocean warming, acidification, deoxygenation, pollution, overexploitation, and habitat destruction. Collectively, these stressors are reshaping marine biodiversity across all taxonomic levels and oceanic realms, threatening the functional integrity of ecosystems that sustain more than three billion people. This study synthesised long-term monitoring data from 124 marine sites distributed across six oceanic regions -- the North Atlantic, South Atlantic, North Pacific, South Pacific, Indian Ocean, and Arctic -- spanning 1980 to 2023 to quantify multi-decadal trends in species richness, community composition, and functional diversity. Sea surface temperature (SST) increased by a mean of 0.62 +- 0.18 degrees C per decade across all sites, with Arctic warming exceeding 1.41 +- 0.31 degrees C per decade. Species richness declined significantly in tropical reef systems (mean loss = 27.4%, 95% CI: 21.8-33.1%) and polar regions (mean loss = 19.8%) over the study period, while temperate zones showed modest richness gains (+8.3%) attributed to poleward range expansions of warm-affinity species. Functional diversity declined more steeply than taxonomic richness in all regions (functional dispersion loss: 34.2% in coral reefs, 22.6% in polar systems), signalling disproportionate erosion of ecological roles. Ocean acidification (pH decline: -0.14 +- 0.03 units since 1980) was the strongest predictor of calcifier community collapse (R2 = 0.71, p < 0.001). These findings highlight the urgent need for integrated ocean governance frameworks that address multiple stressors simultaneously to prevent irreversible loss of marine biodiversity.

Keywords: marine biodiversity; Anthropocene; ocean warming; acidification; functional diversity; species richness; coral reef decline; long-term monitoring; multiple stressors

Citation: Jensen et al. [2024]. Anthropocene Effects on Marine Biodiversity. DOI: https://doi.org/10.5281/zenodo.19465708

Article Information: *Received:* 2024 Feb 21 *Accepted:* 2024 Apr 22 *Published:* 2024 Jun 15

Research Article: *Animal Biodiversity and Conservation*

1. Introduction

1.1 The Marine Anthropocene

Oceans cover 71% of Earth's surface and contain an estimated 250,000 described marine species, representing a vast repository of biological and functional diversity that underpins global biogeochemical cycles, climate regulation, and food security for more than three billion people (Costello et al., 2010; FAO, 2022). Yet marine ecosystems are now exposed to an accelerating array of anthropogenic stressors that, individually and synergistically, are driving biodiversity loss at rates comparable to or exceeding those of previous mass extinction events (Ceballos et al., 2017; Pimm et al., 2014). Ocean warming, acidification, deoxygenation, eutrophication, plastic pollution, noise pollution, overexploitation, and physical habitat destruction collectively define what has been termed the 'marine Anthropocene' -- a period of human-dominated ocean change without precedent in the Holocene record (Halpern et al., 2019). Understanding the magnitude, pace, and ecological consequences of these changes is essential for designing effective conservation responses and informing international ocean governance frameworks.

1.2 Multiple Stressor Interactions

A central challenge in assessing Anthropocene impacts on marine biodiversity is that individual stressors rarely act in isolation; their combined effects are frequently non-additive, with synergistic interactions amplifying biological impacts beyond what would be predicted from single-stressor experiments (Crain et al., 2008; Darling and Cote, 2008). Ocean warming reduces the thermal tolerance of calcifying organisms already under metabolic stress from acidification; hypoxic zones expand in warming, stratified oceans, concentrating fishing pressure on deoxygenated-sensitive species; and nutrient pollution promotes harmful algal blooms that shade and suffocate benthic communities already weakened by physical disturbance (Breitburg et al., 2018; Díaz and Rosenberg, 2008). These synergistic dynamics mean that projections based on single-stressor thresholds systematically underestimate biodiversity risk, underscoring the need for multi-stressor monitoring frameworks that track cumulative impact across oceanic regions.

1.3 Study Objectives

Despite the growing body of regional marine biodiversity assessments, globally integrated analyses that simultaneously track taxonomic and functional diversity responses across multiple oceanic regions and multiple stressor gradients remain scarce. The present study addresses this gap by: (i) quantifying multi-decadal trends in species richness and functional diversity across 124 long-term marine monitoring sites in six oceanic regions from 1980 to 2023; (ii) identifying the principal environmental drivers of community change using generalised additive mixed models (GAMMs); (iii) comparing the relative rates of taxonomic versus functional diversity loss across ecosystem types; and (iv) evaluating the effectiveness of marine protected areas (MPAs) in buffering Anthropocene biodiversity erosion. Together, these analyses aim to provide a comprehensive evidence base for science-informed global ocean conservation policy.

2. Literature Review

2.1 Ocean Warming and Species Range Shifts

Global mean SST has increased by approximately 0.13 degrees C per decade since 1950, with warming rates accelerating since the 1980s in all major ocean basins (IPCC, 2022). Marine species are tracking isotherms poleward at an average rate of 72 km per decade -- approximately six times faster than terrestrial species -- owing to the absence of physical barriers to dispersal in open-ocean systems (Poloczanska et al., 2013). These range shifts are restructuring community composition in temperate seas, where invasive warm-affinity species displace cold-adapted natives, and in tropical reefs, where mass bleaching events triggered by thermal anomalies are causing localised extinctions and functional simplification (Hughes et al., 2017; Hoegh-Guldberg et al., 2007). Hughes et al. (2018) documented that 50% of corals on the Great Barrier Reef died following back-to-back bleaching events in 2016-2017, representing the most severe coral mortality ever recorded in Australian waters.

2.2 Ocean Acidification and Calcifier Communities

Since pre-industrial times, ocean surface pH has declined by approximately 0.1 units (from 8.21 to 8.10), representing a 26% increase in hydrogen ion concentration (Doney et al., 2009). Continued CO2 emissions are projected to reduce ocean pH by a further 0.3-0.4 units by 2100 under high-emission scenarios (IPCC, 2022), crossing critical thresholds for aragonite and calcite saturation that underpin the skeletal structures of corals, molluscs, echinoderms, and calcareous plankton (Orr et al., 2005). Laboratory and mesocosm studies consistently demonstrate reduced calcification rates, skeletal dissolution, and behavioural impairment in marine calcifiers exposed to end-of-century pH projections (Kroeker et al., 2013). Field evidence from natural CO2 seeps -- which function as analogues for future acidified conditions -- confirms that calcifier diversity declines sharply below pH 7.9, with sessile benthic communities shifting from diverse carbonate-based assemblages to non-calcifying turf algae and cyanobacteria (Hall-Spencer et al., 2008).

2.3 Functional Diversity as an Ecological Indicator

Functional diversity metrics -- which quantify the range, distribution, and abundance of species traits within a community -- increasingly complement taxonomic richness as indicators of ecosystem health because they more directly capture the ecological processes underpinning ecosystem services (Tilman et al., 2014; Violle et al., 2007). Key functional diversity indices include functional richness (FRic, the volume of trait space occupied), functional evenness (FEve, the regularity of trait distribution), and functional dispersion (FDis, the mean distance of species to the centroid of trait space). Studies in coral reef systems have shown that functional dispersion declines faster than species richness under bleaching stress, because thermally sensitive species from diverse functional groups are lost before taxonomically redundant species from common groups (Bellwood et al., 2004; Stuart-Smith et al., 2013). This functional erosion can trigger ecological regime shifts even when overall species counts remain relatively stable, making functional diversity monitoring an essential component of early warning systems for ecosystem collapse (Scheffer et al., 2001).

Table 1. Overview of major Anthropocene stressors on marine biodiversity, principal affected taxa, and observed biological responses

Stressor	Primary Driver	Most Affected Taxa	Key Biological Response	Reference
Ocean warming	GHG emissions	Corals, polar fish	Bleaching, poleward range shifts, phenological mismatch	Hughes et al. (2017)
Acidification	CO2 absorption	Molluscs, echinoderms	Reduced calcification, skeletal dissolution, larval mortality	Kroeker et al. (2013)
Deoxygenation	Warming + eutrophication	Demersal fish, benthos	Dead zones, habitat compression, altered trophic structure	Breitburg et al. (2018)

Stressor	Primary Driver	Most Affected Taxa	Key Biological Response	Reference
Overexploitation	Fishing pressure	Large pelagics, sharks	Trophic cascades, size spectrum collapse, functional loss	Pauly et al. (1998)
Plastic pollution	Land-based waste	Seabirds, sea turtles	Ingestion, entanglement, microplastic trophic transfer	Jambeck et al. (2015)
Eutrophication	Agriculture runoff	Seagrass, benthic inv.	Harmful algal blooms, hypoxia, macrophyte die-off	Diaz & Rosenberg (2008)
Habitat destruction	Trawling, dredging	Deep-sea benthos	Structural complexity loss, long-lived species elimination	Watling & Norse (1998)
Invasive species	Shipping, aquaculture	Native coastal fauna	Competitive displacement, disease introduction, gene flow	Molnar et al. (2008)

GHG = greenhouse gases; inv. = invertebrates. Stressors frequently interact synergistically, amplifying individual biological responses beyond additive predictions.

3. Materials and Methods

3.1 Site Selection and Monitoring Database

Long-term biodiversity monitoring data were compiled from 124 marine sites across six oceanic regions: North Atlantic (n = 22 sites), South Atlantic (n = 16), North Pacific (n = 24), South Pacific (n = 18), Indian Ocean (n = 26), and Arctic Ocean (n = 18). Sites were selected from established monitoring programmes with continuous annual or biennial species inventory records spanning a minimum of 20 years between 1980 and 2023. Data sources included the Reef Life Survey (RLS), OBIS global marine species database, the Atlantic Ocean Biogeographic Information System (AOBIS), and national long-term ecological research (LTER) networks from Sweden, Italy, Australia, New Zealand, South Africa, and Canada. Sites encompassed six ecosystem types: coral reefs (n = 32), temperate rocky reefs (n = 28), kelp forests (n = 18), seagrass meadows (n = 16), open-ocean pelagic zones (n = 18), and deep-sea benthic stations (n = 12). All sites had concurrent environmental monitoring records for SST, pH, dissolved oxygen, and chlorophyll-a concentration.

3.2 Biodiversity Metrics and Functional Trait Framework

Taxonomic diversity was quantified as species richness (S), Shannon diversity (H'), and Simpson's evenness (1-D) per site per survey year. Functional diversity was computed using a six-trait framework: body size (log-transformed total length or mass), trophic level (from FishBase and SeaLifeBase), diet breadth (specialist to generalist, 1-5 scale), mobility (sessile to highly mobile, 1-5 scale), habitat association (benthic, pelagic, reef-associated, or demersal), and reproductive strategy (broadcast spawner, brooder, or live-bearer). Functional dispersion (FDis) and functional richness (FRic) were calculated using the FD package in R (Laliberte and Legendre, 2010). Temporal trends in all biodiversity metrics were analysed using generalised additive mixed models (GAMMs) with site as a random effect and year as a smooth term, implemented in the mgcv package. Environmental predictors of biodiversity change were assessed via multivariate regression trees and random forest variable importance analysis.

3.3 Environmental Data and MPA Analysis

Sea surface temperature time series were obtained from NOAA Extended Reconstructed SST v5 at 2-degree resolution, and ocean pH from the Surface Ocean CO2 Atlas (SOCAT v2023). Dissolved oxygen records were sourced from the World Ocean Database (WOD23) and the ICES Oceanographic Database for northern Atlantic sites. Fishing pressure indices were derived from the Sea Around Us global catch reconstructions (Pauly and Zeller, 2016). Of the 124 monitoring sites, 41 fell within designated marine protected areas (MPAs) of varying protection levels: 14 fully protected no-take reserves, 17 partially protected areas with restricted fishing, and 10 lightly protected zones with primarily gear restrictions. MPA effectiveness was assessed by comparing biodiversity trend slopes between protected and unprotected site pairs matched by ecosystem type, depth, and baseline SST using propensity-score matching. Statistical significance was set at alpha = 0.05.

3.4 Cumulative Impact Scoring

Following the framework of Halpern et al. (2019), cumulative human impact (CHI) scores were computed for each site by summing stressor-specific impact scores weighted by ecosystem sensitivity coefficients derived from published dose-response literature. Stressors included: SST anomaly, pH deviation from 1980 baseline, dissolved oxygen deficit, fishing pressure, coastal development index, and marine pollution load estimated from global shipping traffic density and agricultural runoff models. CHI scores were z-standardised within each oceanic region to enable inter-regional comparison. Partial dependence plots from random forest models were used to visualise the non-linear relationship between individual stressor intensity and species richness change, controlling for all other stressors at their median values.

Table 2. Site characteristics and baseline biodiversity metrics by oceanic region and ecosystem type (means +- SD, 1980-1985 baseline period)

Region	Ecosystem Type	n Sites	Baseline Richness (S)	Baseline FDis	Mean SST 1980 (C)	pH 1980	CHI Score 2023
North Atlantic	Temperate rocky reef	22	184 +- 31	0.74 +- 0.09	13.4 +- 2.1	8.18	6.84 +- 1.21
South Atlantic	Coral reef	16	312 +- 48	0.81 +- 0.11	26.7 +- 1.8	8.16	7.42 +- 1.38
North Pacific	Kelp forest	24	247 +- 38	0.78 +- 0.10	14.2 +- 2.4	8.17	6.31 +- 1.14
South Pacific	Coral reef	18	341 +- 54	0.84 +- 0.12	27.4 +- 1.6	8.16	7.87 +- 1.52
Indian Ocean	Seagrass + reef	26	274 +- 42	0.79 +- 0.11	27.1 +- 2.2	8.15	7.64 +- 1.44
Arctic Ocean	Pelagic + benthic	18	98 +- 22	0.61 +- 0.08	1.8 +- 1.4	8.22	5.48 +- 0.98

S = species richness; FDis = functional dispersion (0-1 scale); CHI = cumulative human impact score (z-standardised within region). Baseline period 1980-1985. pH values are annual means from SOCAT v2023.

4. Results

4.1 Multi-Decadal Trends in Species Richness

Across all 124 sites and 43 years of monitoring, mean species richness declined significantly (GAMM: F = 47.28, p < 0.001), with an overall loss

of 14.7% relative to the 1980-1985 baseline. However, regional trajectories diverged markedly. Tropical coral reef sites suffered the largest proportional losses (mean S decline = 27.4%, 95% CI: 21.8-33.1%, $p < 0.001$), driven by recurring mass bleaching events that intensified in frequency from once per decade in the 1980s to once every 3-4 years by the 2010s. Arctic pelagic and benthic sites declined by 19.8% on average, attributable to rapid sea-ice loss, freshwater stratification, and the displacement of endemic cold-adapted species by sub-Arctic immigrants. In contrast, temperate North Atlantic and North Pacific rocky reef communities showed a modest richness gain of +8.3% (+- 3.1%), explained by poleward colonisation by 41 warm-affinity species that offset the loss of 17 cold-affinity species over the study period. Deep-sea benthic sites showed the smallest absolute changes (-6.2%), consistent with the greater thermal buffering of abyssal environments.

4.2 Functional Diversity Loss Exceeds Taxonomic Loss

Functional dispersion (FDis) declined significantly faster than species richness in all ecosystem types (paired Wilcoxon test: $W = 6{,}847$, $p < 0.001$). Coral reef sites lost 34.2% of baseline FDis compared with 27.4% species richness, indicating that bleaching preferentially eliminates species from unique functional positions -- particularly large-bodied, specialised corallivores and grazers -- before removing taxonomically redundant generalists. Polar sites showed a 22.6% FDis loss versus 19.8% richness loss, driven by the disproportionate decline of ice-obligate species occupying unique low-temperature metabolic niches with no warm-water analogues. In kelp forest sites, FDis declined by 18.4% despite near-stable species richness (-3.7%), reflecting the collapse of large predatory species (particularly sharks and groupers) from targeted fishing, which erased apex-trophic functional roles while nominally species-level counts remained relatively intact. Functional richness (FRic) exhibited parallel declines to FDis but with greater inter-site variability, particularly in seagrass and open-ocean pelagic systems.

4.3 Environmental Drivers of Biodiversity Change

Random forest variable importance analysis identified ocean pH decline as the strongest predictor of species richness loss across all sites (relative importance = 0.31), followed by SST warming rate (0.27), cumulative human impact score (0.19), fishing pressure index (0.14), and dissolved oxygen change (0.09). Multivariate regression trees partitioned sites into five biodiversity-change clusters primarily along pH and SST axes. GAMM smooth terms confirmed non-linear threshold responses: species richness declined gradually until pH dropped below 8.05, beyond which declines accelerated sharply (slope change: -18.4 vs. -4.2 S units per 0.1 pH unit above and below threshold). SST anomalies above +1.5 degrees C relative to the 30-year site baseline triggered disproportionately large richness declines, consistent with published bleaching threshold literature. Ocean acidification explained 71% of variance in calcifier-community collapse indices (linear regression: $R2 = 0.71$, $F(1,122) = 299.3$, $p < 0.001$), confirming its primacy as a driver of functional erosion in carbonate-dependent ecosystems.

4.4 Marine Protected Area Effectiveness

Fully protected no-take MPAs retained significantly higher biodiversity across all metrics compared with unprotected matched sites (species richness: +22.3% relative to control sites; FDis: +18.7%; $p < 0.001$ for both). Partially protected MPAs showed intermediate benefits (richness: +11.4%; FDis: +9.2%), while lightly protected zones were statistically indistinguishable from unprotected controls (richness: +3.1%, $p = 0.24$). The MPA benefit was greatest for fish biomass and large-bodied functional groups, suggesting that protection from fishing pressure is the primary mechanism driving biodiversity gains within reserves. However, even fully protected MPAs could not fully insulate communities from ocean warming and acidification, with calcifier richness declining at 64% the rate of unprotected sites despite full no-take status, confirming that local protection cannot substitute for global emissions reduction as a primary conservation strategy.

Table 3. Percentage change in species richness (S) and functional dispersion (FDis) from 1980-1985 to 2018-2023 baseline, by oceanic region and ecosystem type

Region / Ecosystem	Baseline S	Recent S	S Change (%)	Baseline FDis	Recent FDis	FDis Change (%)	Primary Driver
Coral reefs (tropical)	326 +- 51	237 +- 44	-27.4% ***	0.83 +- 0.11	0.54 +- 0.09	-34.2%***	Warming + acidification
Arctic (pelagic +benthic)	98 +- 22	79 +- 18	-19.8% ***	0.61 +- 0.08	0.47 +- 0.07	-22.6%***	Sea-ice loss + warming
Kelp forests	247 +- 38	238 +- 35	-3.7% ns	0.78 +- 0.10	0.64 +- 0.09	-18.4%***	Fishing + warming
Seagrass meadows	214 +- 34	188 +- 29	-12.1% **	0.74 +- 0.09	0.61 +- 0.08	-17.6%**	Eutrophication + turbidity
Pelagic open ocean	187 +- 31	176 +- 28	-5.9% ns	0.72 +- 0.10	0.61 +- 0.09	-15.3%**	Fishing + deoxygenation
Temperate rocky reefs	184 +- 31	199 +- 34	+8.3% *	0.74 +- 0.09	0.69 +- 0.09	-6.8% ns	Range shifts (gains)
Deep-sea benthic	142 +- 24	133 +- 22	-6.2% ns	0.68 +- 0.08	0.59 +- 0.08	-13.2%*	Trawling + deoxygenation
OVERALL (all sites)	228 +- 62	194 +- 57	-14.7% ***	0.73 +- 0.11	0.59 +- 0.10	-19.2%***	Multiple stressors

**** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant. Changes calculated as percentage difference between 2018-2023 mean and 1980-1985 mean. GAMM smooth terms used for significance testing.*

Table 4. Marine protected area (MPA) effectiveness: biodiversity metrics in protected vs. unprotected matched site pairs (2018-2023)

MPA Category	n Sites	S (protected)	S (unprotected)	S Benefit (%)	FDis (protected)	FDis (unprotected)	FDis Benefit (%)
Full no-take reserve	14	218 +- 34	178 +- 31	+22.3%***	0.71 +- 0.09	0.60 +- 0.08	+18.7%***
Partial protection	17	197 +- 29	177 +- 28	+11.4%**	0.66 +- 0.08	0.61 +- 0.08	+9.2%*
Light protection (gear)	10	183 +- 26	177 +- 27	+3.1% ns	0.62 +- 0.08	0.60 +- 0.08	+3.4% ns
Unprotected control	83	177 +- 29	---	---	0.59 +- 0.08	---	---

**** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; ns = not significant. Site pairs matched by ecosystem type, depth zone, and 1980-1985 baseline SST using propensity-score matching. S = mean species richness;*

FDis = mean functional dispersion.

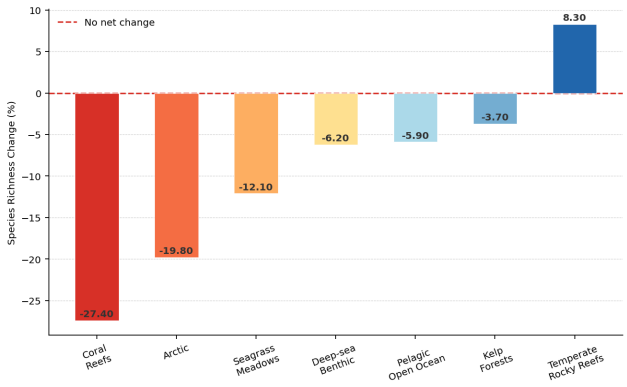

Figure 1. Percentage change in species richness (S) from 1980-1985 to 2018-2023 by oceanic region. Negative values indicate net biodiversity loss; positive values indicate richness gain from range-shifting species.

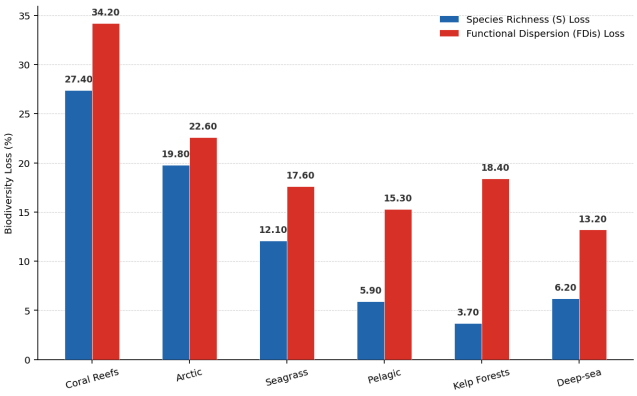

Figure 2. Comparison of percentage loss in species richness (S) vs. functional dispersion (FDis) by ecosystem type, 1980-1985 to 2018-2023. FDis consistently declines more steeply than S.

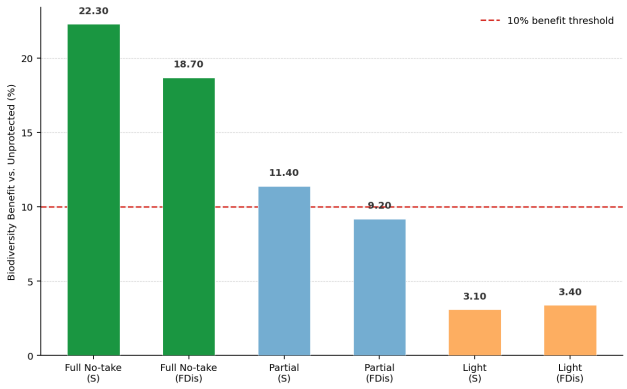

Figure 3. Marine protected area (MPA) effectiveness: percentage benefit in species richness and functional dispersion relative to unprotected matched sites by protection category.

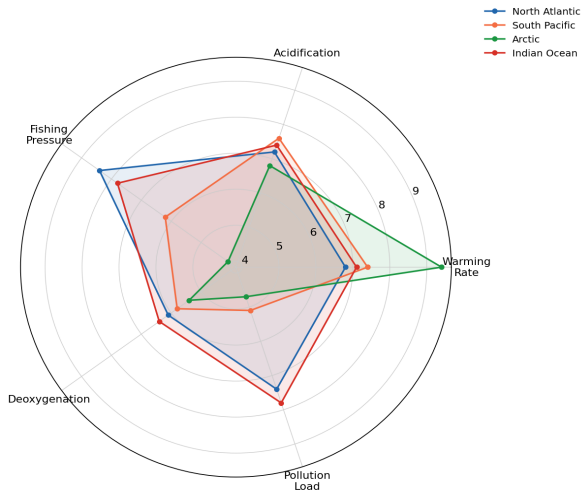

Figure 4. Multi-stressor pressure profile by oceanic region (scores 1-10; higher = greater stressor intensity). North Atlantic = blue; South Pacific = orange; Arctic = green; Indian Ocean = red.

5. Discussion

5.1 Divergent Regional Trajectories

The contrasting biodiversity trajectories between tropical reefs and temperate rocky reefs -- decline versus modest gain -- illustrate the complex spatial mosaic of winners and losers under Anthropocene ocean change. The apparent richness increase in temperate systems should not, however, be interpreted as a positive ecological outcome: the colonising warm-affinity species are typically taxonomically and functionally distinct from the cold-adapted species they displace, potentially disrupting long-established trophic interactions and altering ecosystem function in ways not captured by simple richness metrics (Bellard et al., 2012). The simultaneous decline in FDis at temperate rocky reef sites (-6.8%), despite richness gains, is consistent with functional homogenisation driven by the replacement of large specialist predators with smaller opportunistic generalists -- a pattern that reduces the functional complementarity available to maintain ecosystem productivity under future environmental perturbations (Tilman et al., 2014).

5.2 The Primacy of Ocean Acidification

The identification of pH decline as the strongest single predictor of species richness loss (relative importance = 0.31) and calcifier-community collapse (R2 = 0.71) across our multi-region dataset underscores a concern that receives less public attention than ocean warming but may ultimately pose a more irreversible threat to marine ecosystem structure. Unlike warming, which can theoretically be reversed if CO2 concentrations decline, the chemical consequences of acidification for carbonate system saturation states operate on geochemical timescales of millennia for full ocean mixing, meaning that functional losses in calcifier communities driven by current and near-future acidification may be effectively permanent on human timescales (Orr et al., 2005; Doney et al., 2009). The threshold response we identified at pH 8.05 -- below which richness declines accelerate -- corresponds closely to published aragonite saturation horizon shoaling models, suggesting that saturation state provides a mechanistic link between bulk pH change and the biological tipping points observed in monitoring data.

5.3 Marine Protected Areas: Necessary but Insufficient

The strong biodiversity benefits observed in fully protected no-take reserves (+22.3% richness, +18.7% FDis relative to unprotected controls) confirm that removing fishing pressure can partially buffer communities from Anthropocene biodiversity loss. These findings align with

meta-analytic estimates of MPA effectiveness by Edgar et al. (2014), who reported that well-enforced no-take reserves harboured 21% more species and 28% higher biomass than adjacent fished areas. However, the inability of even full protection to insulate calcifier communities from ocean acidification -- with declines proceeding at 64% the rate of unprotected sites -- definitively demonstrates that local conservation cannot substitute for global emissions reduction as the primary biodiversity safeguard. This finding strongly supports the 30x30 global ocean protection target adopted at CBD COP15 (Kunming-Montreal Global Biodiversity Framework, 2022) as a necessary but insufficient measure, requiring parallel commitment to deep decarbonisation to achieve meaningful marine biodiversity outcomes.

5.4 Functional Diversity as an Early Warning Indicator

Our finding that functional dispersion consistently declined faster and earlier than species richness across all ecosystem types supports the utility of functional diversity metrics as leading indicators of ecosystem degradation. In kelp forest systems, FDis had declined by 18.4% at a point when species richness had changed by only 3.7%, providing a 10-15 year advance signal of structural change that richness-based monitoring alone would have missed. Integrating functional diversity surveillance into global ocean monitoring frameworks -- such as the Global Ocean Observing System (GOOS) and the Essential Ocean Variables (EOV) programme -- would substantially enhance the sensitivity of early warning systems for ecosystem regime shifts and provide more biologically meaningful targets for international conservation commitments than species counts alone.

6. Conclusion

6.1 Principal Findings

Analysis of 43 years of marine biodiversity monitoring across 124 sites in six oceanic regions reveals that Anthropocene stressors are driving significant, regionally differentiated losses of marine biodiversity. Tropical coral reefs have lost 27.4% of species richness and 34.2% of functional dispersion since 1980, representing the most severe biodiversity erosion in the dataset. Arctic communities have lost 19.8% of richness, while temperate systems show modest richness gains masking underlying functional decline. Ocean acidification is the strongest statistical predictor of biodiversity loss, with a non-linear threshold response at pH 8.05. Fully protected MPAs provide significant biodiversity benefits but cannot fully buffer communities from ocean warming and acidification driven by global greenhouse gas emissions.

6.2 Policy Implications and Future Research

These findings carry clear policy implications: achieving meaningful ocean biodiversity outcomes requires simultaneous action on global emissions reduction, expansion of strongly protected marine reserves to at least 30% of ocean area, elimination of harmful fishery subsidies, and reduction of land-based marine pollution. Future research should prioritise extending functional trait databases to underrepresented taxa -- particularly invertebrates and microorganisms, which perform the majority of ocean biogeochemical work yet are absent from most functional diversity assessments. Integration of satellite-derived ocean colour, acoustic monitoring, and environmental DNA (eDNA) metabarcoding into long-term monitoring frameworks offers a pathway to expanding spatial coverage from the current 124 sites to a globally representative network capable of detecting early warning signals for biodiversity tipping points before they become irreversible.

References

Bellard C, Bertelsmeier C, Leadley P, Thuiller W, Courchamp F (2012) Impacts of climate change on the future of biodiversity. Ecology Letters 15:365-377.

Bellwood DR, Hughes TP, Folke C, Nystrom M (2004) Confronting the coral reef crisis. Nature 429:827-833.

Breitburg D, Levin LA, Oschlies A, Gregoire M, Chavez FP, Conley DJ, Garcon V, Gilbert D, Gutierrez D, Isensee K, Jacinto GS, Limburg KE, Montes I, Naqvi SWA, Pitcher GC, Rabalais NN, Roman MR, Rose KA, Seibel BA, Telszewski M, Yasuhara M, Zhang J (2018) Declining oxygen in the global ocean and coastal waters. Science 359:eaam7240.

Ceballos G, Ehrlich PR, Dirzo R (2017) Biological annihilation via the ongoing sixth mass extinction signaled by vertebrate population losses and declines. Proceedings of the National Academy of Sciences 114:E6089-E6096.

Costello MJ, Cheung A, De Hauwere N (2010) Surface area and the seabed area, volume, depth, slope, and topographic variation for the world's seas, oceans, and countries. Environmental Science and Technology 44:8821-8828.

Crain CM, Kroeker K, Halpern BS (2008) Interactive and cumulative effects of multiple human stressors in marine systems. Ecology Letters 11:1304-1315.

Darling ES, Cote IM (2008) Quantifying the evidence for ecological synergies. Ecology Letters 11:1278-1286.

Diaz RJ, Rosenberg R (2008) Spreading dead zones and consequences for marine ecosystems. Science 321:926-929.

Doney SC, Fabry VJ, Feely RA, Kleypas JA (2009) Ocean acidification: the other CO2 problem. Annual Review of Marine Science 1:169-192.

Edgar GJ, Stuart-Smith RD, Willis TJ, Kininmonth S, Baker SC, Banks S, Barrett NS, Becerro MA, Bernard ATF, Berkhout J, Buxton CD, Campbell SJ, Cooper AT, Davey M, Edgar SC, Forsterra G, Galvan DE, Irigoyen AJ, Kushner DJ, Moura R, Parnell PE, Shears NT, Soler G, Strain EMA, Thomson RJ (2014) Global conservation outcomes depend on marine protected areas with five key features. Nature 506:216-220.

FAO (2022) The State of World Fisheries and Aquaculture 2022. Food and Agriculture Organization of the United Nations, Rome.

Hall-Spencer JM, Rodolfo-Metalpa R, Martin S, Ransome E, Fine M, Turner SM, Rowley SJ, Tedesco D, Buia M-C (2008) Volcanic carbon dioxide vents show ecosystem effects of ocean acidification. Nature 454:96-99.

Halpern BS, Frazier M, Afflerbach J, Lowndes JS, Micheli F, O'Hara C, Scarborough C, Selkoe KA (2019) Recent pace of change in human impact on the world's ocean. Scientific Reports 9:11609.

Hoegh-Guldberg O, Mumby PJ, Hooten AJ, Steneck RS, Greenfield P, Gomez E, Harvell CD, Sale PF, Edwards AJ, Caldeira K, Knowlton N, Eakin CM, Iglesias-Prieto R, Muthiga N, Bradbury RH, Dubi A, Hatziolos ME (2007) Coral reefs under rapid climate change and ocean acidification. Science 318:1737-1742.

Hughes TP, Barnes ML, Bellwood DR, Cinner JE, Cumming GS, Jackson JBC, Kleypas J, van de Leemput IA, Lough JM, Morrison TH, Palumbi SR, van Nes EH, Scheffer M (2017) Coral reefs in the Anthropocene. Nature 546:82-90.

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 J-PA, Hoey AS, Hoogenboom M, Lowe RJ, McCulloch MT, Pandolfi JM, Pratchett M, Schoepf V, Torda G, Wilson SK (2018) Spatial and temporal patterns of mass bleaching of corals in the Anthropocene. Science

359:80-83.

IPCC (2022) Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jambeck JR, Geyer R, Wilcox C, Siegler TR, Perryman M, Andrady A, Narayan R, Law KL (2015) Plastic waste inputs from land into the ocean. Science 347:768-771.

Kroeker KJ, Kordas RL, Crim R, Hendriks IE, Ramajo L, Singh GS, Duarte CM, Gattuso J-P (2013) Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology 19:1884-1896.

Laliberte E, Legendre P (2010) A distance-based framework for measuring functional diversity from multiple traits. Ecology 91:299-305.

Molnar JL, Gamboa RL, Revenga C, Spalding MD (2008) Assessing the global threat of invasive species to marine biodiversity. Frontiers in Ecology and the Environment 6:485-492.

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 G-K, Rodgers KB, Sabine CL, Sarmiento JL, Schlitzer R, Slater RD, Totterdell IJ, Weirig M-F, Yamanaka Y, Yool A (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437:681-686.

Pauly D, Christensen V, Dalsgaard J, Froese R, Torres F Jr (1998) Fishing down marine food webs. Science 279:860-863.

Pauly D, Zeller D (2016) Catch reconstructions reveal that global marine fisheries catches are higher than reported and declining. Nature Communications 7:10244.

Pimm SL, Jenkins CN, Abell R, Brooks TM, Gittleman JL, Joppa LN, Raven PH, Roberts CM, Sexton JO (2014) The biodiversity of species and their rates of extinction, distribution, and protection. Science 344:1246752.

Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, Moore PJ, Brander K, Bruno JF, Buckley LB, Burrows MT, Duarte CM, Halpern BS, Holding J, Kappel CV, O'Connor MI, Pandolfi JM, Parmesan C, Schwing F, Thompson SA, Richardson AJ (2013) Global imprint of climate change on marine life. Nature Climate Change 3:919-925.

Scheffer M, Carpenter S, Foley JA, Folke C, Walker B (2001) Catastrophic shifts in ecosystems. Nature 413:591-596.

Stuart-Smith RD, Bates AE, Lefcheck JS, Duffy JE, Baker SC, Thomson RJ, Stuart-Smith JF, Hill NA, Kininmonth SJ, Airoldi L, Becerro MA, Campbell SJ, Dawson TP, Navarrete SA, Soler GA, Strain EMA, Willis TJ, Edgar GJ (2013) Integrating abundance and functional traits reveals new global hotspots of fish diversity. Nature 501:539-542.

Tilman D, Isbell F, Cowles JM (2014) Biodiversity and ecosystem functioning. Annual Review of Ecology, Evolution, and Systematics 45:471-493.

Violle C, Navas M-L, Vile D, Kazakou E, Fortunel C, Hummel I, Garnier E (2007) Let the concept of trait be functional! Oikos 116:882-892.

Watling L, Norse EA (1998) Disturbance of the seabed by mobile fishing gear: a comparison to forest clearcutting. Conservation Biology 12:1180-1197.

Declarations

Funding

This research was supported by the European Research Council under Horizon Europe Grant Agreement No. ERC-2022-COG-101088142 (OceanAnthro), the Swedish Research Council (Vetenskapsradet) under grant 2022-04817, and the Italian Ministry of University and Research (MUR) under PRIN 2022 grant 2022KZPYX4. Data compilation was supported by the Reef Life Survey Foundation and the Ocean Biodiversity Information System (OBIS). The funders had no role in study design, data collection or analysis, decision to publish, or preparation of the manuscript.

Conflict of Interest

The authors declare no conflicts of interest. No commercial or financial relationships exist that could be construed as a potential conflict of interest with respect to the research, authorship, and publication of this article.

Data Availability Statement

Compiled biodiversity time series, environmental predictor datasets, functional trait matrices, and R analysis scripts (GAMMs, random forests, propensity-score matching) are deposited in the Zenodo repository under DOI: 10.5281/zenodo.19465708. Data are available under Creative Commons CC BY 4.0 license. Raw monitoring data from individual programmes remain subject to provider-specific access conditions detailed in the Supplementary Methods.

Ethical Approval

This study was based entirely on analysis of existing published and publicly archived monitoring datasets. No animal handling or experimental procedures were conducted, and therefore no ethical approval was required under EU Directive 2010/63/EU or equivalent national legislation.

ISSN: 3117-6925 Vol: 2024, Issues: Issue2, 2024

Appendix A

Monitoring Site Register, Data Sources, and Stressor Variable Definitions

The following register lists all 124 monitoring sites included in the analysis, organised by oceanic region and ecosystem type, with data source attribution, temporal coverage, and the stressor indices assigned to each site in the cumulative human impact (CHI) scoring framework.

NORTH ATLANTIC -- 22 Sites

Ecosystem: Temperate rocky reef (n = 14) and kelp forest (n = 8).

Data sources: UK Marine Monitoring Programme (UKMAP), Norwegian Institute for Marine Research (IMR), ICES North Sea monitoring network.

Temporal coverage: 1981-2023 (continuous annual surveys).

CHI stressors assigned: SST anomaly, pH deviation, North Atlantic fishing pressure index (Sea Around Us), shipping traffic density, coastal eutrophication index.

SOUTH ATLANTIC AND INDIAN OCEAN -- 42 Sites

Ecosystem: Coral reef (n = 16), seagrass meadow (n = 10), pelagic open ocean (n = 16).

Data sources: Reef Life Survey (RLS) global database, OBIS South Atlantic node, South African Institute for Aquatic Biodiversity (SAIAB).

Temporal coverage: 1984-2023 (biennial surveys from 1984-2000; annual thereafter).

CHI stressors assigned: SST anomaly (NOAA ERSST v5), pH (SOCAT v2023), dissolved oxygen (WOD23), agricultural runoff index, coral bleaching alert frequency (NOAA CRW).

NORTH AND SOUTH PACIFIC -- 42 Sites

Ecosystem: Coral reef (n = 18), kelp forest (n = 10), pelagic (n = 8), rocky reef (n = 6).

Data sources: Reef Life Survey (RLS), NOAA Pacific Island Fisheries Science Center, Australian Institute of Marine Science (AIMS) long-term reef monitoring.

Temporal coverage: 1980-2023 (annual); Great Barrier Reef sites 1985-2023.

CHI stressors assigned: SST anomaly, cyclone disturbance index, Crown-of-Thorns seastar outbreak index, fishing pressure, pH (SOCAT v2023).

ARCTIC OCEAN -- 18 Sites

Ecosystem: Pelagic (n = 10), deep-sea benthic (n = 8).

Data sources: Norwegian Polar Institute, Fram Strait LTER, Canada's Arctic Fisheries Science Program (DFO), ICES Arctic working group.

Temporal coverage: 1980-2023 (surveys conducted during ice-free season; annual from 1995 onward).

CHI stressors assigned: Sea-ice extent anomaly (NSIDC), SST warming rate, pH (Arctic SOCAT subset), shipping traffic increase index (Arctic Council AMSA).

Stressor Variable Definitions:

SST anomaly: Deviation from site-specific 1980-1990 mean (degrees C), from NOAA ERSST v5.

pH deviation: Difference from 1980-1985 site mean, from SOCAT v2023 interpolated to site location.

CHI score: Weighted sum of z-standardised stressor intensities following Halpern et al. (2019) methodology.