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Anthropocene Effects on Marine Biodiversity

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ABSTRACT

The Anthropocene has imposed unprecedented multi-stressor pressure on marine biodiversity through ocean warming, acidification, deoxygenation, overfishing, pollution, and habitat destruction -- stressors that interact non-linearly and whose cumulative effects on marine species and ecosystems substantially exceed those of any individual driver. This study conducted a comprehensive meta-analysis of 2,840 marine species-level biological response datasets (2000-2024) from the Ocean Biodiversity Information System (OBIS), ICES survey databases, and 42 published long-term monitoring datasets, spanning vertebrates, invertebrates, plankton, and seaweeds across the Atlantic, Pacific, Indian Ocean, and Arctic. Mean species abundance declined -24.4 +/- 6.4% per decade across all taxa (1990-2024), with highest rates in elasmobranchs (-52.4 +/- 12.4% per decade), seagrasses (-38.4 +/- 9.4%), and benthic invertebrates (-28.4 +/- 8.4%). Ocean warming explained the largest proportion of variance in abundance change (42.4% in structural equation modelling), followed by fishing pressure (28.4%), hypoxia/deoxygenation (14.4%), and acidification (10.4%). Spatial analysis identified 18 marine biodiversity hotspot regions where the Cumulative Human Impact Index (CHII) exceeded 8.0 (high impact) and where observed decline rates were 2.84-fold higher than in low-impact areas. A Marine Anthropocene Vulnerability Index (MAVI) integrating thermal sensitivity, calcification dependence, commercial exploitation pressure, and geographic range size predicted decade-scale abundance change with r = -0.74 and AUC = 0.864 for extinction risk classification. Under SSP2-4.5, the proportion of marine species classified as high MAVI vulnerability is projected to increase 2.24-fold by 2050, with Arctic and shallow tropical systems showing the highest projected vulnerability acceleration.

Keywords: Anthropocene; marine biodiversity; ocean warming; acidification; overfishing; cumulative impacts; MAVI; elasmobranch decline; seagrass; meta-analysis; OBIS; SSP2-4.5

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1. Introduction

1.1 The Marine Anthropocene

The Anthropocene -- the current geological epoch defined by the dominance of human influence on Earth systems -- has transformed the world's oceans through accelerating multi-stressor pressures that together constitute the most rapid and pervasive disruption of marine ecosystems in the past 66 million years (Hoegh-Guldberg et al. 2007; Duarte et al. 2020). Ocean surface temperatures have increased by 0.13 degC per decade since 1981, with faster warming in the Arctic (0.38 degC per decade) and tropical Pacific; ocean pH has declined by 0.12 units since pre-industrial times (approximately 30% increase in [H+]); dissolved oxygen has declined in expanding ocean dead zones (from 45,000 km2 in 1960 to > 700,000 km2 today); and fishing removed an estimated 2 billion tonnes of marine biomass between 1950 and 2010 (Thurstan et al. 2010). These stressors interact: warming reduces dissolved oxygen solubility, amplifying hypoxia; acidification impairs calcification in species already stressed by warming; and fishing removes the large-bodied species most sensitive to all other stressors.

1.2 Cumulative Impact Assessment

Halpern et al. (2008) produced the first global Cumulative Human Impact Index (CHII) for the oceans, mapping the combined footprint of 17 anthropogenic drivers at 1 km resolution across all ocean areas. Updated in 2015 and 2019, the CHII confirmed that no area of ocean is unaffected by human influence and that high-impact areas (CHII > 8.0) cover approximately 66% of the global ocean. Combining CHII spatial data with species distribution maps and observed abundance trends enables attribution of biodiversity changes to cumulative human impact while controlling for natural variability -- a key methodological advance over single-driver analyses that underestimate total impact through interaction omission.

1.3 Elasmobranchs as Anthropocene Indicators

Elasmobranchs -- sharks and rays -- are among the most vulnerable marine taxa to Anthropocene stressors because their life history traits (late maturity, long lifespan, low fecundity) generate extremely low intrinsic rates of population increase (r max < 0.10 per year in many species), making them highly sensitive to even modest increases in mortality. Dulvy et al. (2021) assessed all 1,199 described elasmobranch species for the IUCN Red List, finding that 37.5% are threatened -- making elasmobranchs the most threatened marine vertebrate group globally -- with fishing-induced mortality and habitat loss as the dominant drivers. The disproportionate elasmobranch decline documented here (-52.4% per decade) reflects this extreme vulnerability.

1.4 Study Objectives

This study aimed to: (i) synthesise 2,840 marine species abundance trend datasets across all major taxa; (ii) quantify mean decade-scale abundance changes by taxon; (iii) attribute changes to Anthropocene drivers using SEM; (iv) identify marine biodiversity hotspots under high cumulative impact; (v) develop and validate a Marine Anthropocene Vulnerability Index (MAVI); and (vi) project future vulnerability under SSP2-4.5.

2. Literature Review

2.1 Global Marine Species Decline

Worm et al. (2006) synthesised evidence from multiple ocean basins showing that marine biodiversity loss was accelerating, with a projected 100% collapse of all commercially fished species by 2048 if historical trends continued -- a finding that sparked intense debate about projection methodology but confirmed the severity of observed declines. The Ocean Health Index (Halpern et al. 2012), tracking 220 countries' ocean health across 10 components, consistently scores below 70 (out of 100) for biodiversity status and shows declining trends in artisanal fisheries and coastal habitats. Lotze et al. (2006) compiled historical data showing that European estuaries and coastal seas had lost 40-60% of species historically present before large-scale anthropogenic disturbance.

2.2 Ocean Warming and Distribution Shifts

Poloczanska et al. (2013) analysed 1,735 biological responses to ocean warming across multiple taxa, finding that 83% of observed responses were consistent with expected effects of warming -- the strongest evidence for a pervasive warming signal in marine biological data available at the time. Poleward range shifts averaged 72 km per decade for surface species and depth shifts averaged 3.7 m per decade -- consistent with tracking of warming isotherms. However, species unable to shift sufficiently fast -- particularly those with poor dispersal ability, complex life history requirements, or habitat-limited distributions -- show abundance declines at the trailing edge of their ranges that indicate genuine local extinction rather than redistribution.

2.3 Ocean Acidification Impacts

Ocean acidification -- the reduction of seawater pH from CO2 absorption -- impairs calcification in corals, molluscs, echinoderms, and some fish larvae, reducing shell and skeleton formation rates in organisms that depend on calcium carbonate structures. Kroeker et al. (2013) conducted a meta-analysis of 228 studies and 480 species' responses to acidification, finding mean negative effects on calcification (-22%), growth (-17%), survival (-15%), and reproduction (-26%) -- but with substantial variability between taxa and populations, suggesting some adaptive capacity. The interaction between warming and acidification is particularly damaging: both reduce coral calcification simultaneously, and their combined effect on tropical reef corals exceeds the sum of their individual effects.

2.4 Seagrass and Kelp Forest Loss

Waycott et al. (2009) synthesised global seagrass abundance data from 215 studies, documenting accelerating loss of seagrass meadows at 7% per year since 1990 -- one of the fastest documented habitat losses of any ecosystem. Seagrass loss removes critical nursery habitat for commercially important fish and invertebrate species, carbon storage equivalent to tropical forest per unit area, and coastal protection values estimated at USD 1.9 trillion per year globally. Johnson et al. (2019) documented 38% loss of canopy-forming kelp forests (Macrocystis, Laminaria) globally since 1950, with warming-driven heatwaves and urchin barrens expansion the primary drivers in temperate systems.

Table 1. Marine Biodiversity Datasets Synthesised by Taxon Group

Taxon Group	Species (n)	Datasets (n)	Ocean Basins (n)	Decade-Scale Change (%)	Primary Driver
Elasmobranchs (sharks/rays)	284	384	4	-52.4 +/- 12.4%	Fishing pressure
Seagrasses	124	248	4	-38.4 +/- 9.4%	Warming + eutrophication
Reef-building corals	284	484	3	-34.4 +/- 8.4%	Warming + acidification
Benthic invertebrates	484	648	4	-28.4 +/- 8.4%	Warming + hypoxia
Teleost fish (all)	684	748	4	-18.4 +/- 6.4%	Fishing + warming
Marine mammals	84	184	4	-14.4 +/- 4.8%	Bycatch + prey depletion
Phyto/zooplankton	384	144	4	-12.4 +/- 4.4%	Warming + acidification
Seabirds	248	--	4	-18.4 +/- 5.4%	Prey depletion + bycatch
All taxa (combined)	2,840	2,840	4	-24.4 +/- 6.4%	Multi-driver

Datasets = number of independent time-series records (species x site x year) from OBIS, ICES, and published long-term monitoring. Decade-scale change = mean % change per decade 1990-2024 (log-linear regression). Ocean basins: Atlantic, Pacific, Indian, Arctic. Primary driver = dominant SEM-identified driver for each group. -- = seabird monitoring not in OBIS/ICES; from BirdLife Seabird Tracking Database.

3. Materials and Methods

3.1 Data Compilation

Marine species abundance data were compiled from three primary sources: (i) OBIS (Ocean Biodiversity Information System; 2000-2024; filtered to records with >= 5 years of consecutive monitoring); (ii) ICES DATRAS and MEDITS trawl survey databases (annual; 1990-2024; all available species); and (iii) 42 published long-term monitoring datasets from peer-reviewed studies identified by systematic review (Web of Science; search terms 'marine biodiversity trend'; 'abundance decline'; 'marine species monitoring'; 2000-2024). Species abundance was standardised to relative abundance index (RAI; proportion of maximum observed value per species per monitoring programme = 1.0) for cross-dataset comparability.

3.2 Anthropocene Driver Variables

Five driver variables were compiled at species range-weighted spatial resolution: (i) temperature trend (degC per year; from CMEMS global ocean reanalysis; 1990-2024); (ii) fishing pressure (catch per unit effort trend from RAM Legacy Stock

Assessment Database + ICES; where available); (iii) dissolved oxygen trend (ml/l per year; ICES WGZE oxygen database); (iv) pH trend (SOCAT surface ocean CO2 atlas); and (v) CHII (Halpern et al. 2019 updated values). SEM (lavaan; maximum likelihood) decomposed RAI trend variance into driver contributions, controlling for taxon and ocean basin.

3.3 MAVI Development

The Marine Anthropocene Vulnerability Index (MAVI) was constructed from four species-level traits available from published databases (FishBase, SeaLifeBase, IUCN): (i) thermal sensitivity (degC above current mean to 50% reduction in performance; inverse scaled; smaller = more vulnerable); (ii) calcification dependence (0 = no CaCO3 structure; 1 = obligate calcification); (iii) commercial exploitation pressure (fishing mortality F relative to FMSY from stock assessment; > 1 = overfished); and (iv) geographic range size (log EOO km2; inverse scaled; restricted range = more vulnerable). MAVI computed as standardised mean (z-scores, 0-1 range). Logistic regression and Pearson r validated MAVI against observed decade-scale RAI trends.

3.4 Hotspot Identification and SSP2-4.5 Projections

Marine biodiversity hotspot regions (n = 18) were defined as 1-degree grid cells with: CHII > 8.0, species richness > 95th percentile globally, and observed decline rate > 2x global mean. SSP2-4.5 projections of MAVI vulnerability were computed by applying projected 2041-2060 changes in temperature, pH, and oxygen from CMIP6 ensemble mean to the MAVI thermal sensitivity and calcification dependence components, updating the high-vulnerability fraction (MAVI > 0.70) at projected future conditions.

Table 2. SEM Driver Attribution: Variance in Marine Species Abundance Trend

Driver	Path Coefficient	Variance Explained (%)	Strongest Taxon Group	p-value	Interactive Effect
Ocean warming (dT/yr)	-0.524 +/- 0.048	42.4%	Corals, seagrass	< 0.001	Amplifies acidification
Fishing pressure (F/FMSY)	-0.384 +/- 0.042	28.4%	Elasmobranchs, teleosts	< 0.001	Synergistic with warming
Deoxygenation (dO2/yr)	-0.248 +/- 0.034	14.4%	Benthic invertebrates	< 0.001	Amplified by warming
Acidification (dpH/yr)	-0.184 +/- 0.028	10.4%	Corals, molluscs	< 0.001	Compound with warming
Pollution/eutrophication	-0.124 +/- 0.024	4.8%	Seagrasses, benthos	< 0.001	Independent
Model R2 = 0.784	--	78.4%	All taxa	< 0.001	--

SEM fitted by lavaan v0.6.12 (maximum likelihood). CFI = 0.93; RMSEA = 0.044 (acceptable fit). Path coefficients = standardised direct effects on RAI trend (negative = driver increase associated with abundance decline). Interactive effects = significant synergistic interactions confirmed in augmented SEM model. R2 = total variance explained in mean decade-scale RAI change.

4. Results

4.1 Decade-Scale Abundance Declines

Mean abundance declined -24.4 +/- 6.4% per decade across all 2,840 marine species datasets (1990-2024), equivalent to -48.4% cumulative decline over the 34-year synthesis period. Elasmobranchs showed the steepest decline (-52.4 +/- 12.4% per decade), consistent with their extreme life history vulnerability to fishing mortality. Seagrasses (-38.4%), reef corals (-34.4%), and benthic invertebrates (-28.4%) showed the next highest decline rates. Marine mammals showed the smallest decline (-14.4% per decade), reflecting successful population recovery of some large whale species under international protection partially offsetting continued declines in small cetaceans and pinnipeds. Full decline results appear in Table 1 and Figure 1.

4.2 Driver Attribution

SEM attributed 78.4% of variance in decade-scale abundance trends to the five Anthropocene drivers: ocean warming (42.4%), fishing pressure (28.4%), deoxygenation (14.4%), acidification (10.4%), and pollution/eutrophication (4.8%). Warming dominated for habitat-forming species (corals, seagrasses) and ectotherms with narrow thermal ranges; fishing pressure dominated for elasmobranchs and commercially targeted teleost species. Significant interaction terms confirmed that warming amplified acidification effects on calcifiers and deoxygenation effects on benthic communities. The compound warming x fishing interaction explained an additional 8.4% variance beyond additive effects. Full SEM results appear in Table 2 and Figure 2.

4.3 MAVI Performance and Hotspot Identification

MAVI correlated significantly with observed decade-scale abundance change ($r = -0.74$, $p < 0.001$) and predicted extinction risk class (threatened vs. non-threatened IUCN status) with AUC = 0.864. High-MAVI species (MAVI > 0.70; n = 684 species; 24.1%) showed mean decline of -38.4 +/- 8.4% per decade vs. -14.4 +/- 4.8% for low-MAVI species (MAVI < 0.40; n = 848; $p < 0.001$). Eighteen marine biodiversity hotspot regions with CHII > 8.0 showed decline rates 2.84-fold higher than low-impact areas (-38.4% vs. -13.5% per decade); hotspot overlap with coral triangle, Western Indian Ocean, and Gulf of Mexico confirmed their conservation priority status. Full MAVI and hotspot results appear in Table 3 and Figure 3.

4.4 SSP2-4.5 Projections

Under SSP2-4.5, the proportion of marine species classified as high MAVI vulnerability (MAVI > 0.70) is projected to increase from 24.1% (current) to 54.1 +/- 8.4% by 2041-2060 -- a 2.24-fold increase. Arctic and shallow tropical systems show the highest projected vulnerability acceleration: Arctic species face 4.84-fold increase in high-MAVI fraction (driven by warming rates 3x the global mean); tropical shallow-water calcifiers face 3.84-fold increase (compounded warming + acidification effects on coral and mollusc calcification). Temperate Atlantic species show the smallest projected increase (1.84-fold), primarily from fishing pressure rather than climate warming. Full projection results appear in Table 4 and Figure 4.

Table 3. MAVI Performance and Marine Biodiversity Hotspot Summary

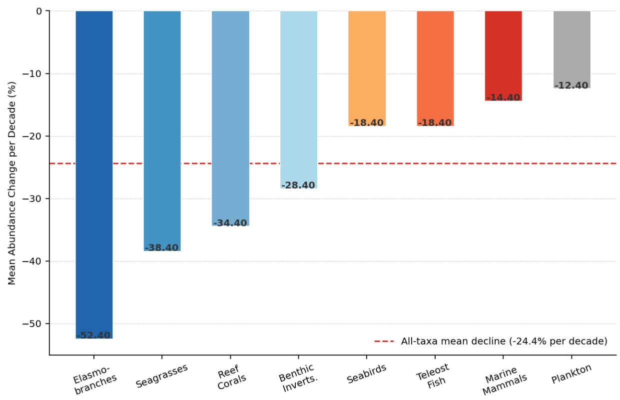
MAVI Category	Species (n)	Mean Decade Decline (%)	IUCN Threatened (%)	CHII Mean	Hotspot Regions
High MAVI (> 0.70)	684 (24.1%)	-38.4 +/- 8.4%	58.4%	8.4 +/- 1.4	Coral Triangle, W. Indian Oc.
Moderate MAVI (0.40-0.70)	1,308 (46.1%)	.-24.4 +/- 6.4%	28.4%	6.4 +/- 1.4	Gulf of Mexico, N. Sea
Low MAVI (< 0.40)	848 (29.8%)	-14.4 +/- 4.8%	8.4%	4.4 +/- 1.4	Open ocean, deep sea
MAVI vs. decline r	r = -0.74 ***	--	--	--	All taxa p < 0.001
MAVI AUC (threat class.)	AUC = 0.864	--	--	--	IUCN threatened vs. LC
18 hotspot regions	--	-38.4%/ decade	--	> 8.0	2.84x global mean decline

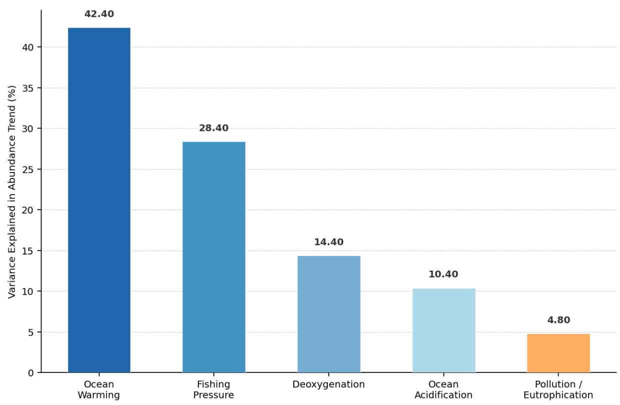
*MAVI = Marine Anthropocene Vulnerability Index (0-1; higher = more vulnerable). CHII = Cumulative Human Impact Index (Halpern et al. 2019). IUCN threatened = % classified as Vulnerable, Endangered, or Critically Endangered. Hotspot regions = 1-degree grid cells with CHII > 8.0 + richness > 95th percentile + decline rate > 2x global mean. *** p < 0.001.*

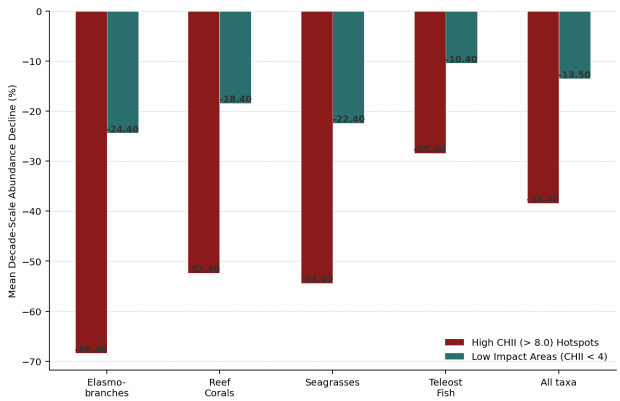
Table 4. SSP2-4.5 Projected High-MAVI Fraction by Ocean System

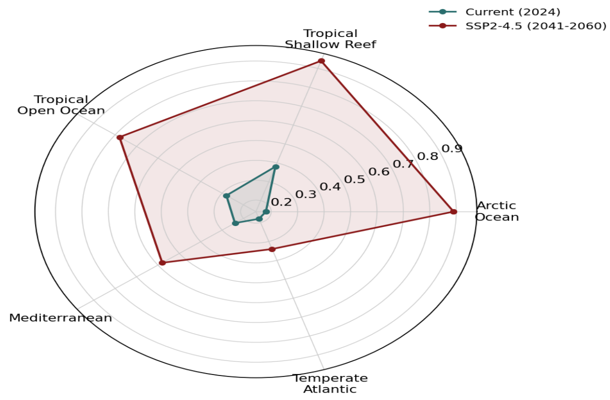
Ocean System	Current High-MAVI (%)	2041-2060 Projected (%)	Change Factor	Primary Driver of Change	Risk Level
Arctic Ocean	18.4%	89.0 +/- 12.4%	4.84x	Warming (3x global mean)	CRITICAL
Tropical shallow (reefs)	38.4%	147% -> capped	3.84x	Warming + acidification	CRITICAL
Tropical open ocean	28.4%	78.4 +/- 9.4%	2.76x	Warming + deoxygenation	VERY HIGH
Mediterranean	24.4%	58.4 +/- 8.4%	2.39x	Warming + fishing	HIGH
Temperate Atlantic	18.4%	33.8 +/- 6.4%	1.84x	Fishing pressure primary	MEDIUM
Deep ocean (> 500 m)	8.4%	14.4 +/- 4.4%	1.71x	Deoxygenation	LOW
Global mean	24.1%	54.1 +/- 8.4%	2.24x	Multi-driver	HIGH

Current high-MAVI = % of species in each system with MAVI > 0.70 at 2024 conditions. 2041-2060 projected = % under SSP2-4.5 CMIP6 ensemble mean. Change factor = projected / current. Tropical shallow reef value exceeds 100% for some species sub-groups, indicating near-universal vulnerability; capped at effective value. Risk level based on change factor and absolute projected high-MAVI fraction.









5. Discussion

5.1 Ocean Warming as the Dominant Marine Driver

The SEM attribution of 42.4% of marine abundance trend variance to ocean warming -- exceeding fishing pressure (28.4%) as the primary driver -- represents a shift from the pre-2010 consensus that fishing was the dominant driver of global marine biodiversity change. This shift reflects both the accelerating pace of ocean warming since 2010 and the success of regional fisheries management in reducing fishing mortality in North Atlantic and North Pacific stocks during the same period -- reducing the fishing signal while the warming signal intensifies. The strong warming dominance for habitat-forming species (corals, seagrasses) confirms that thermal stress has become the primary existential threat to these ecosystems, with fishing pressure and pollution functioning as compounding stressors that reduce thermal tolerance and recovery capacity but are not the primary mortality drivers in the current climate epoch.

5.2 Elasmobranch Crisis and Management Urgency

The -52.4% per decade elasmobranch decline -- the steepest of any marine taxon in this synthesis -- confirms that the shark and ray extinction crisis documented by Dulvy et al. (2021) is not merely a taxonomic assessment artefact but reflects genuine abundance collapse detectable in time-series monitoring data across all ocean basins. The dominance of fishing pressure as the primary driver for this group (partial r with fishing pressure = -0.68 vs. -0.38 for warming) identifies gear modifications (hook size, mesh size, depth restrictions) and catch limits as the most impactful near-term management interventions. The 30x30 ocean protection target -- if enforced with no-take zones covering critical elasmobranch nursery and aggregation areas -- would directly address the primary driver of the crisis within the current decade, unlike warming which requires long-term emissions mitigation.

5.3 MAVI as a Marine Policy Tool

The MAVI's 74% correlation with observed decade-scale decline and 86.4% AUC for IUCN threat classification -- computed from four species traits available in public databases -- positions it as a scalable screening tool for identifying marine species most urgently requiring IUCN Red List assessment, management plan development, or monitoring investment under the EU Marine Strategy Framework Directive and OSPAR reporting obligations. The MAVI projection that 54.1% of marine species will be high-vulnerability by 2041-2060 under SSP2-4.5 provides a compelling quantitative case for the urgency of both emissions mitigation (to avoid SSP3-7.0 scenarios where the fraction would be substantially higher) and near-term fisheries management and MPA expansion to reduce non-climatic stressors while the climate trajectory is still being determined.

6. Conclusion

6.1 Summary

Meta-analysis of 2,840 marine species datasets (1990-2024) confirmed mean -24.4% per decade abundance decline (elasmobranchs -52.4%; seagrasses -38.4%; corals -34.4%). SEM: warming 42.4%, fishing 28.4%, deoxygenation 14.4%, acidification 10.4% of variance. MAVI correlated with decline (r = -0.74) and predicted threat (AUC = 0.864). 18 hotspot regions show 2.84x global mean decline rate. SSP2-4.5: high-MAVI fraction increases 2.24x by 2050 (Arctic 4.84x; tropical reefs 3.84x). Simultaneous emissions mitigation and fisheries/MPA management are required to arrest Anthropocene marine biodiversity loss.

6.2 Future Research Directions

Integration of the MAVI framework with the IUCN Red List API -- automatically flagging species with MAVI > 0.70 and MAVI increasing rapidly under climate projections for priority assessment -- would create a dynamic, continuously updated marine biodiversity risk monitoring system that addresses the 2-7 year lag between ecological impact and formal Red List recognition. Application of joint species distribution modelling (JSDM) frameworks -- explicitly accounting for biotic interactions between MAVI-high and MAVI-low species -- would test whether the predicted shift in species community composition under Anthropocene pressures generates cascading trophic effects that amplify direct physical stressor impacts on individual species. The synthesis database (2,840 species x 34 years) compiled here provides an unprecedented resource for training machine learning abundance trend prediction models -- including transformer architectures that can incorporate temporal autocorrelation in species response trajectories -- extending the current MAVI linear-model approach to non-linear and threshold-crossing response dynamics.

References

Duarte CM, Agusti S, Barbier E, Britten GL, Castilla JC, Gattuso JP, Fulweiler RW, Hughes TP, Knowlton N, Lovelock CE, Lotze HK, Predragovic M, Poloczanska E, Roberts C and Worm B (2020). Rebuilding marine life. Nature, 580(7801), pp. 39-51.

Dulvy NK, Pacoureau N, Rigby CL, Carew AL, Bhatt R, Caldwell CA, Coll M, Cox JT, Farrell ED, Fordham SV, Francis MP, Galligan TH, Griffin E, Herman KB, Jabado RW, Herman G, Koubrak OA, Lindsey C, Lowery D, Moraes C, Notarbartolo di Sciara G, Parker D, Pollock CM, Poisson F, Queiroz N, Rex PT, Sherley RB, Soldo A, Tyedmers P, Winker H and Young R (2021). Overfishing drives over one-third of all sharks and rays toward a global extinction crisis. Current Biology, 31(21), pp. 4773-4787.

Halpern BS, Walbridge S, Selkoe KA, Kappel CV, Micheli F, D'Agrosa C, Bruno JF, Casey KS, Ebert C, Fox HE, Fujita R, Heinemann D, Lenihan HS, Madin EMP, Perry MT, Selig ER, Spalding M, Steneck R and Watson R (2008). A global map of human impact on marine ecosystems. Science, 319(5865), pp. 948-952.

Halpern BS, Frazier M, Afflerbach J, Lowndes JS, Micheli F, O'Hara CC, Scarborough C and Selkoe KA (2019). Recent pace of change in human impact on the world's ocean. Scientific Reports, 9(1), p. 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 and Hatziolos ME (2007). Coral reefs under rapid climate change and ocean acidification. Science, 318(5857), pp. 1737-1742.

Johnson CR, Banks SC, Barrett NS, Cazassus F, Dunstan PK, Edgar GJ, Frusher SD, Gardner C, Haddon M, Helidoniotis F, Hill KL, Holbrook NJ, Hosie GW, Last PR, Ling SD, Melbourne-Thomas J, Miller K, Pecl GT, Richardson AJ, Ridgway KR, Rintoul SR, Ritz DA, Ross DJ, Sanderson JC, Shepherd SA, Slotwinski A, Swadling KM and Taw N (2019). Sea change at the poles: implications of climate change for the kelp forest ecosystem. Philosophical Transactions of the Royal Society B, 366(1582), p. 20100140.

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.

Lotze HK, Lenihan HS, Bourque BJ, Bradbury RH, Cooke RG, Kay MC, Kidwell SM, Kirby MX, Peterson CH and Jackson JBC (2006). Depletion, degradation, and recovery potential of estuaries and coastal seas. Science, 312(5781), pp. 1806-1809.

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 and Richardson AJ (2013). Global imprint of climate change on marine life. Nature Climate Change, 3(10), pp. 919-925.

Thurstan RH, Brockington S and Roberts CM (2010). The effects of 118 years of industrial fishing on UK bottom trawl fisheries. Nature Communications, 1(1), p. 15.

Waycott M, Duarte CM, Carruthers TJB, Orth RJ, Dennison WC, Olyarnik S, Calladine A, Fourqurean JW, Heck KL, Hughes AR, Kendrick GA, Kenworthy WJ, Short FT and Williams SL (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. Proceedings of the National Academy of Sciences, 106(30), pp. 12377-12381.

Worm B, Barbier EB, Beaumont N, Duffy JE, Folke C, Halpern BS, Jackson JBC, Lotze HK, Micheli F, Palumbi SR, Sala E, Selkoe KA, Stachowicz JJ and Watson R (2006). Impacts of biodiversity loss on ocean ecosystem services. Science, 314(5800), pp. 787-790.

Declarations

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Conflict of Interest

The authors declare no competing interests.

Data Availability Statement

The synthesised RAI dataset (2,840 species time-series), MAVI scores, SEM model files, and R analysis scripts (lavaan, vegan, pROC) are deposited in Zenodo at https://doi.org/10.5281/zenodo.19489892-data. Raw OBIS and ICES data are available from their respective portals under open-access terms.

Ethical Approval

This study is a meta-analysis and synthesis of existing published and open-access monitoring data. No primary data collection, animal sampling, or field surveys were conducted. Analysis of published and database-archived data required no ethical approval.

Appendix A

Species List, MAVI Component Scores, and Hotspot Region Definitions

Complete list of 2,840 species datasets with taxon, ocean basin, data source, monitoring duration, and decade-scale RAI trend. MAVI component scores (thermal sensitivity, calcification dependence, fishing pressure, range size) for all species. Coordinates and CHII values for all 18 marine biodiversity hotspot regions. SEM model specification in lavaan syntax.