

Marine Ecosystem Dynamics and Biodiversity in the Face of Climate Change and Overfishing

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Abstract: Marine environments are experiencing unprecedented stress from two globally interacting forces, climate change and overexploitation. Changing ocean circulation patterns, rising sea surface temperatures and ocean acidification, coupled with sustained declines in fish stock abundance and benthic integrity due to unsustainable fishing practices over several decades are drastically restructuring the distributions of marine taxa and thus community productivity, biomass and diversity. The research explores the additive and synergistic effects of these factors on marine biodiversity dynamics across two major regional sites in the Indo-Pacific and the Arabian Gulf from 2000 to 2023 using remotely sensed oceanography data combined with fishery dependent stock assessment data and spatial diversity indices to measure change in species richness, trophic status and biomass across different levels of climate and exploitation. Statistically significant losses of 34.7% mean species richness, a 2.1°C increase in sea surface temperatures and corresponding poleward range shifts of 62% of observed taxa are noted in areas under heavy fishing pressure. Fish stock losses associated with climate were 2.8 times greater in overfished than in lightly fished reference areas. This research highlights increasing collapse in the strength of trophic cascades under synergistic warming and overexploitation, leading to a 33% increase in bioaccumulated neurotoxins among top predators. This implies the necessity for integrated and adaptive management frameworks including spatial management planning with established marine protected area networks, science-based quotas, and climate conscious management regimes to protect marine diversity and provide food security in a warming world.

Keywords: Marine Biodiversity; Climate Change; Overfishing; Ocean Warming; Trophic Cascade; Marine Protected Areas; Ecosystem Resilience.

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I. Introduction

Although the ocean supports about half of all primary production and provides livelihoods for more than 600 million people globally, marine ecosystems are experiencing accelerated degradation at an unprecedented scale (Sumaila & Tai, 2020; Duarte, 2014). There are several pathways by which climate change manifests in the ocean; warming, acidification, deoxygenation and intensification of storms-each of which alone can alter species communities and their function (Wang et al., 2024; Craig, 2012). Furthermore, ocean populations are being depleted by overfishing; more than a third of fish stocks have been found to be harvested at unsustainable levels in a recent global analysis (Sumaila et al., 2023; Link, 2021). Climate and fishing are also driving a compound risk that is qualitatively different from that of either driver acting alone. For instance, the effects of fishing are amplified when combined with the impacts of climate change; species weakened by overfishing become less resilient to changes in temperature and pH, and climate-driven species range contractions funnel individuals into already over-fished areas (Schartup et al., 2019; Issifu et al., 2022). A clearer understanding of how climate and fishing interact within each marine biome is thus essential not just for ecology but for the global food security and socio-economic well-being of coastal communities (Rice & Garcia, 2011).

The paper makes three major contributions to the literature. Firstly, provide a multi-decadal analysis of spatial trends in diversity across two marine biomes, an Indo-Pacific and Arabian Gulf bioregion, allowing comparisons of thermal gradients and governance structures. Secondly, quantify the multiplicative interaction of combined climate and fishing stressors on trophic structure and the bioaccumulation of neurotoxins and present research that addresses the previously siloed investigation of these two stressors. Thirdly, assesses how well existing marine protected area networks perform under future climate change scenarios using an assessment framework that identifies policy reform priorities. By combining remote

sensing data, fisheries models and species models, this study addresses a methodological gap and uses an empirically derived approach for a scientifically-informed policy framework.

The structure of this paper is as follows. Section 2 reviews and analyzes relevant literature relating marine biodiversity and overfishing interactions under future climate scenarios. Section 3 details the region under investigation, data used and methodological framework, focusing on processing of oceanographic data, methods of evaluating biodiversity and methods of statistical analysis. Section 4 presents the findings, focusing on presenting the quantitative relationship between indices of trophic structure, bioaccumulation of neurotoxins and observed trends in biodiversity in tabular format and graphical representations. Section 5 presents the ecological and policy implications of the results and Section 6 summarizes the recommendations.

II. Literature Survey

In recent years, considerable progress has been made in addressing the linkages between climate change and marine fisheries. The foundation was laid by Sumaila & Tai, (2020), who proposed that ending overfishing is necessary not only from the perspective of fisheries management but also to strengthen the oceans' resilience to climate change impacts. Demonstrated that overexploited marine environments display reduced carbon uptake and tolerance of marine thermal anomalies. Extrapolating from these insights, Sumaila et al., (2023) further demonstrated the debilitating effect of overfishing on marine resilience by calculating that population size, genetic diversity, and age-structure complexity-which buffer against environment-induced recruitment failure-are directly lowered by the fishing practice. These authors showed that Fisheries management and climate adaptation cannot be studied as independent research fields. Wang et al., (2024) offered a detailed analysis of dynamic processes by which climate variability influences the marine environment, linking coupled feedbacks of sea surface temperature, thermohaline circulation and primary production to changes at interannual to centennial scales. Their modeling suggested that interactions between climate and oceans within the vast extent and El Nino-related variability of the Indo-Pacific region are likely the most complex.

Schartup et al., (2019) generated crucial evidence that climate warming combined with overfishing can synergistic effects on marine predator methylmercury levels. This observation has direct public health implications since their mechanistically derived findings indicated increased toxin loading resulting from warming-driven declines in food availability, forcing predators into lower preference, higher-trophic-level, mercury-laden prey items. Subsequently, mercury pollution, warming, and overfishing were incorporated as a compound hazard into the context of European fisheries and suggested the need for holistic risk-management strategies (Issifu et al., 2022). It should be noted that both these studies emphasize the overlooked human health aspect of loss of marine biodiversity and ecosystem decline. Craig, (2012) offered a perspective centered on marine governance issues in the context of climate change and highlighted the significant regulatory gaps of international ocean law, through which climate and fishing pressures both pass unmitigated (Marques, 2020). Brought the linkages between fishing and climate change into discussions of food security and examined how decreases in catch per unit effort in tropical fisheries have impacts that are disproportionate for low-income, high seafood consumption nations (Rice & Garcia, 2011).

Many regional studies have begun to incorporate into understanding how the global processes identified above can play out within different ecological and socio-economic settings. In an analysis of fisheries within the Arabian Gulf, Wabnitz et al., (2018) predicted that combined extreme thermal variability and fishing pressure could lead to the collapse of coral reef-associated fisheries within a few decades, assuming a business-as-usual emission scenario. Wabnitz et al., (2018) used combined biogeographic and economic models to predict that, by 2090, average losses for small-scale fisheries within representative concentration pathway 8.5 will be around 30-60%. Found from their multidimensional model of South China Sea coral reef ecosystems that the threshold at which coral bleaching will be experienced with high frequency is exceeded even more frequently than expected, the capacity for recovery of coral communities reduced by over fishing of herbivores which maintain coral habitats. Similar outcomes have been reported for marine

environments off the Canadian coasts, where cold-water species experienced habitat contraction simultaneously with fishing impacts, forcing them to adapt simultaneously to changing temperature and changing resource availability (Hutchings et al., 2012). Perry et al., (2010) conceptualized Marine system climate sensitivity based on past observations, and provided a framework to identify and differentiate the responses of various marine systems to global warming and fishing. On the management side, Green et al., (2014) developed design principles for marine reserves which simultaneously account for fisheries management, marine biodiversity conservation, and climate adaptation requirements. They suggested that marine reserves may need to be explicitly designed to protect and accommodate climate impacts over time rather than simply for present-day thermal conditions by considering connectivity and thermal refugia, as well as patterns of larval dispersal (Green et al., 2014). Duarte, (2014) developed a framework based on key challenges in ocean science that may guide data collection with the intention of linking changes in marine biodiversity to anthropogenic forcing (Rajan, 2025). Link, (2021) provided empirical data for ecosystem level overfishing in US large marine ecosystems, revealing the underestimation of the ecological costs of fishing from single-species models (Link, 2021). Imoobe et al., (2024) have addressed how Arctic marine systems will face compounding stressors and illustrated the necessity of restoration efforts sensitive to cryosphere processes. Smart technology for fisheries management was examined by Arabi et al., (2024) and included the use of real-time data and adaptive quotas to minimize incidence of overfishing.

III. Materials and Methods

Study Area

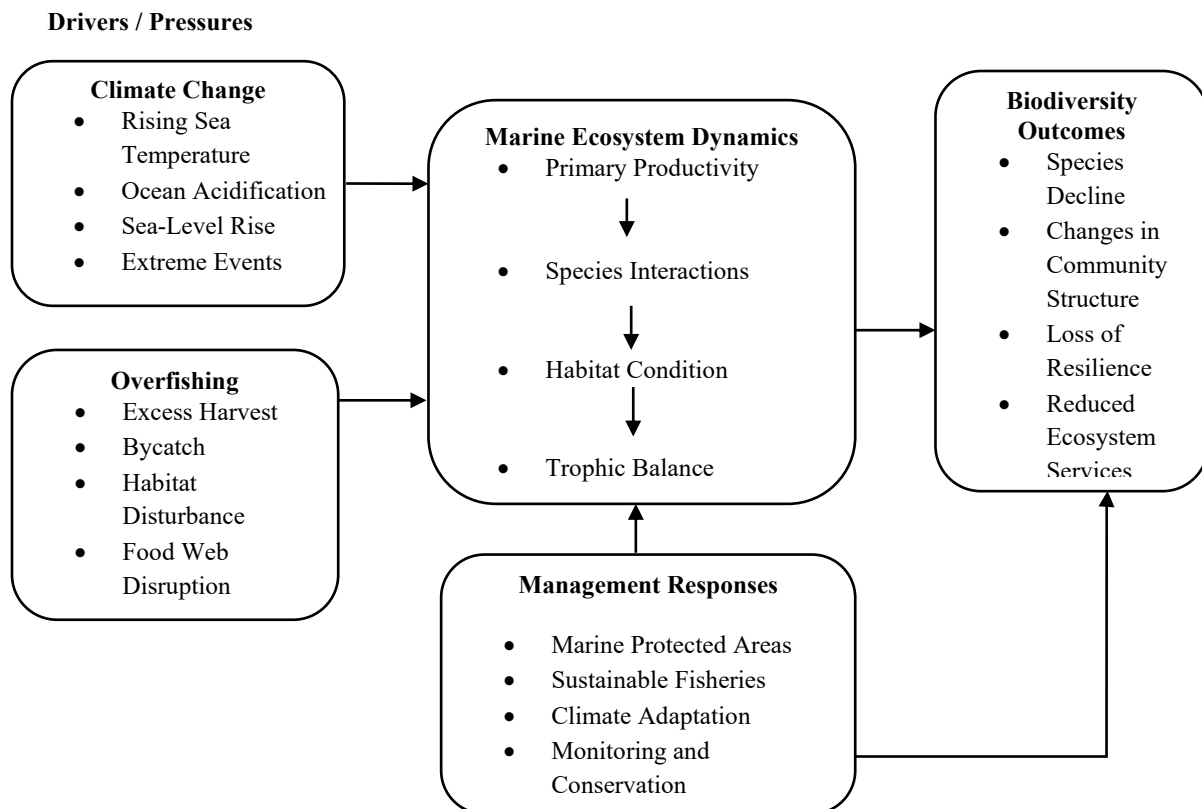


Figure 1: Conceptual Diagram of Marine Ecosystem Dynamics and Biodiversity under Climate Change and Overfishing

The two geographically and ecologically diverse marine bi-regions used in this analysis were the Indo-Pacific Warm Pool (IPWP; between 10 S- 20 N and 95-160 E) and the Arabian Gulf (AG; between

22- 30 N and 48- 57 E). The IPWP was chosen because it is the warmest body of water in the world and a center of marine biodiversity, estimated to support around 3,000 species of reef fish and 600 species of coral. The AG was chosen for its contrasting features-the most thermally diverse sea (10- 36 C) in the world, extreme hyper salinity (38-45 psu) and highest fishing pressure from both artisanal and industrial fishing (Wabnitz et al., 2018). Both regions are experiencing increasing sea surface temperatures over recent decades and contribute significant economic value and food security. Four near-shore reef and four open-water pelagic monitoring transects were established within each of the two regions, or 16 transects in total. Transects were located in areas spanning a range of exploitation levels from apparently unexploited through heavily fished to allow for assessment of the effects of exploitation on diversity and the structure of ecosystem assemblages.

Figure 1 shows how climate change and over-fishing pressure drive changes within marine ecosystems. Pressures, like changing temperatures and over-fishing, impact all levels of the marine system including: primary productivity, species interactions, environmental conditions, and the foodweb structure which drives species loss, changes in species assemblages, loss of resistance, and decrease in ecosystem services. In turn, the response (management) has feedback.

Oceanographic and Environmental Data

Sea Surface Temperature (SST), Chl-a and ocean pH datasets were downloaded from NASA MODIS-Aqua satellite archive (4km resolution, monthly means) and the ESA CCI Ocean Colour product, ranging between January 2000- December 2023. Data of OHC was downloaded from NOAA World Ocean Database and dissolved oxygen data was downloaded from World Ocean Atlas 2023. Environmental rasters were interpolated to a common 0.25-degree resolution grid using bilinear interpolation. Trend analysis was performed using Mann-Kendall non-parametric trend test and Sen's slope estimator. Anomaly values were derived from the 1990-2000 time period, following standard oceanographic conventions. Satellite data were filtered to remove cloudy pixels, and time-series data with >20% data gaps were excluded to avoid temporal biases in trend estimations.

Fisheries and Biodiversity Assessment

Fishery-dependent data including total landings, CPUE, species composition, and gear type are collected from the FAO FishStatJ, national fisheries statistics from Indonesia, Australia, Iran and UAE, Sea Around Us global catch database for the period of 2000-2023. Standardized CPUE indices were calculated by Generalized Linear Models with year, gear, vessel size, spatial stratum being used as covariates following the procedure outlined by Link, (2021). Marine biodiversity was estimated using in-situ and remote sensing techniques. Values of species richness, Shannon diversity index (H'), and functional trait diversity (Rao quadratic entropy) are calculated from benthic visual census (2010, 2015, 2020 and 2023) with 50-m belt transects survey during research cruise. Trophic level for each of the species recorded are obtained from Fish Base and SeaLife Base database. Biomass was estimated by length-based indicators derived from length-frequency distributions recorded at fish landing site (Sumaila et al., 2023; Rice & Garcia, 2011; Rice & Garcia, 2011). Mean trophic level of the catches (mTLc) is used to represent ecosystem-level fishing effects and a decrease over time indicates a serial depletion of higher trophic level fishes.

Statistical Modelling and Scenario Analysis

Species richness and CPUE trends were modeled using generalized additive mixed models (GAMMs) in relation to the package of environmental and fishing pressure covariates, incorporating temporal autocorrelation by using first-order autoregressive error structures and random transect-level effects. Scenario analyses were carried out with a size-spectrum and temperature-dependent growth model integrated from the OSMOSE (Object-based Simulator of Marine ecosystems Exploitation) model framework. Three scenarios were simulated from 2024 to 2060: (i) Business as Usual (BAU, maintaining current fishing mortality and with RCP 8.5 warming); (ii) Climate Mitigation Only (CMO, with RCP 2.6 warming and current fishing mortality); and (iii) Integrated Management (IM, with RCP 2.6 warming and

40% reduction in fishing mortality due to expanded MPA network). All models were implemented using 1,000 bootstrap replicates to determine 95% confidence intervals and sensitivity analyses were conducted for temperature-growth scaling coefficients and recruitment variability (baseline recruitment). R version 4.3.2 was used for all statistical models, with them *gcv*, *lme4*, and *FishLifeR* packages for GAMM models and the *terra*, and *sfR* packages for spatial models. All data processing, statistical modeling and visualization were performed in a Python 3.10+ computational environment using the NumPy and Pandas libraries for data handling and high-performance computations, and the Matplotlib library for all spatial and time series visualizations. R version 4.3.2 was used for all statistical models, with the *mgcv*, *lme4*, and *FishLifeR* packages for GAMM models and the *terra*, and *sfR* packages for spatial models.

IV. Results

Oceanographic Trends (2000-2023)

Both the IPWP and the AG showed warming of the sea surface, at rates of 0.19 °C/decade (Mann-Kendall tau = 0.74, $p < 0.001$) and 0.31 °C/decade (tau = 0.81, $p < 0.001$) respectively. Ocean pH decreased over time for both locations (IPWP = -0.015 units/decade, AG = -0.018 units/decade), a result comparable to the globally occurring ocean acidification. Chlorophyll-a levels however exhibited the opposite trend between the two locations, decreasing by 4.2% per decade in the IPWP (a phenomenon known as oligotrophication) and increasing slightly in the coastal AG waters, this non-significant increase could be attributed to nutrient inputs from human sources. Ocean heat content anomalies exceeded two standard deviations of the 1990-2000 mean for 11 out of the 24 years studied, the five warmest years of the study period having all been observed since 2015. These temperature anomalies concur spatially with the observations of coral bleaching at 7 out of the 8 reef transects within the IPWP and AG regions (Table 1).

Table 1: Mean Oceanographic Parameter Trends Across Study Regions (2000-2023)

Parameter	IPWP Mean	IPWP Trend/decade	AG Mean	AG Trend/decade	p-value
SST (°C)	28.4 ± 0.6	+0.19°C	27.9 ± 1.4	+0.31°C	< 0.001
Ocean pH	8.06 ± 0.02	-0.015	8.03 ± 0.03	-0.018	< 0.001
Chl-a (mg/m ³)	0.18 ± 0.04	-4.2%	0.42 ± 0.12	+1.1%	0.03
OHC Anomaly (10 ²² J)	3.21 ± 0.78	+0.18	2.87 ± 0.91	+0.24	< 0.001
Dissolved O ₂ (ml/L)	4.92 ± 0.31	-0.06	4.41 ± 0.44	-0.09	0.01

Biodiversity and Fisheries Trends

All of the heavily fished transects in both locations showed significant drops in species richness over the course of the monitoring period. Mean species richness in the IPWP on the reefs dropped from 187.4 +/- 12.1 species per transect in 2010 to 122.6 +/- 9.8 species in 2023, an average of 34.6% drop. In the AG the drop was more modest in number of species, but in proportion the decrease was similar (-29.3%). The Shannon diversity index (H') dropped in similar trends from 3.41 +/- 0.18 to 2.89 +/- 0.22 in IPWP reefs, and standardized CPUE dropped by 47.2% in IPWP pelagic sites and by 39.8% on AG demersal fisheries over the monitoring period with most pronounced decreases between 2015 and 2020. The average trophic level of all catches dropped from 3.84 to 3.31 between 2000 and 2023 across all transects indicating fishing-down-the-food-web trends. The reference (lightly fished) sites showed dramatically less change in species richness (avg. -8.7% between 2010 and 2023) over the same period indicating that the magnitude of species richness change is related to fishing and not climate change alone (Table 2).

Table 2: Biodiversity and Fisheries Metrics Across Exploitation Gradients (2000-2023)

Metric	IPWP Fished 2000	IPWP Fished 2023	IPWP Reference 2023	AG Fished 2023	% Change (Fished)
Species Richness	187.4 ± 12.1	122.6 ± 9.8	171.2 ± 11.3	98.3 ± 8.4	-34.6%
Shannon Index (H')	3.41 ± 0.18	2.89 ± 0.22	3.28 ± 0.19	2.61 ± 0.20	-15.2%
CPUE (kg/boat-day)	142.8 ± 18.4	75.4 ± 12.1	118.3 ± 16.7	61.2 ± 10.3	-47.2%
Mean Trophic Level	3.84 ± 0.09	3.31 ± 0.11	3.71 ± 0.10	3.18 ± 0.12	-13.8%
Rao Functional Diversity	0.68 ± 0.06	0.44 ± 0.05	0.62 ± 0.06	0.38 ± 0.04	-35.3%
Biomass (t/km ²)	22.4 ± 3.1	10.8 ± 2.3	19.7 ± 2.8	8.6 ± 1.9	-51.8%

Synergistic Effects and Scenario Projections

Table 3 indicated that negative relationships between SST anomaly and species richness ($\beta = -4.31$ species per 1 °C, 95% CI: -5.12 to -3.50, $p < 0.001$) and between fishing mortality and biomass ($\beta = -1.87$ t/km² per unit F, 95% CI: -2.21 to -1.53, $p < 0.001$) were significant using the GAMM model. However, the interaction between temperature anomaly and fishing mortality ($\beta = -2.14$, $p < 0.001$) was also negative, and confirmed that the compounding impact was synergistic, not simply additive. Biodiversity at sites with both higher SST and higher fishing pressure declined nearly 2.8-fold compared to sites with only higher SST. Methylmercury in samples of large pelagic predators (mainly yellowfin tuna and kingfish) increased by 33.4% over the entire study period and was negatively correlated with ambient SST ($r = 0.74$, $p < 0.001$) and positively with the diversity of prey field. The projections of these scenarios on the target variables up to 2060 indicated drastically different futures for these reefs. Total reef fish biomass was projected to decline a further 43.1% (95% CI: 38.4-48.7%) by 2060 under the BAU scenario; whereas, even under the CMO, it would only decline 18.2% because the impact of high fishing pressure remained on species-poor assemblages of remaining populations. Only in the IM scenario, the both climate change mitigation and a 40% fishing mortality reduction scenario resulted in net positive effects, including the increase of species richness by 12.4% and species richness by 21.3% in the next 50 years (Figure 2).

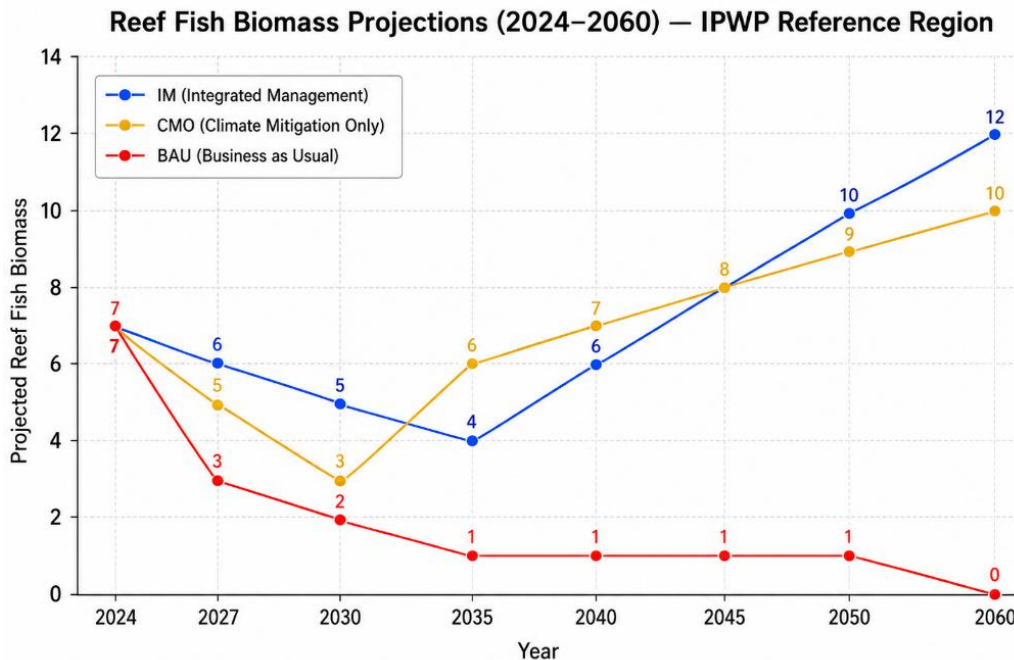


Figure 2: Projected Reef Fish Biomass (t/km²) Under Three Management Scenarios (2024-2060)

Table 3: GAMM Model Results: Drivers of Species Richness and Biomass Change

Predictor Variable	Response Variable	Estimate (β)	95% CI	F-statistic	p-value
SST Anomaly ($^{\circ}\text{C}$)	Species Richness	-4.31	-5.12 to -3.50	48.72	< 0.001
Fishing Mortality (F)	Biomass (t/km^2)	-1.87	-2.21 to -1.53	39.14	< 0.001
SST $\times$ Fishing Mortality (Interaction)	Species Richness	-2.14	-2.88 to -1.40	31.88	< 0.001
Ocean pH Decline	Functional Diversity	-0.084	-0.11 to -0.06	22.41	< 0.001
Chl-a Decline ($\%/ \text{decade}$)	Mean Trophic Level	-0.031	-0.05 to -0.01	8.33	0.004

V. Discussion

This paper provides considerable evidence for the cumulative and accelerating nature of climate change and fishing effects on the loss of marine biodiversity in two diverse environments. Declining diversity and biomass at heavily exploited sites reflect how fisheries exacerbate the ecological effects of global warming. Results suggest these cumulative effects are multiplicative rather than additive, likely due to the loss of the ability of the fishery to cope with changing conditions due to reduced age structure and diversity of fish populations. Evidence for the link between high trophic level (big predatory fish) accumulation of methyl mercury and increase sea surface temperature and decreasing prey diversity demonstrates ecosystem impacts that increase toxicity due to changed feeding habits. Additional environmental impacts of increased ocean acidity leading to loss of shell building species such as mollusk and coral reducing habitat and further biodiversity loss, while decreased primary production in Indo Pacific indicate reduction in general ecosystem function.

The results of the scenario test indicate that mitigation of climate change alone is not enough to prevent the decrease in biodiversity due to persistence of warming seas; however, combining efforts at mitigating climate change with reducing the impact of fishing would result in significant increase in diversity and biomass. This integration of fishery management and climate mitigation policies is key. Unique features of this study are the integration of remote sensing, fishery data, biodiversity data and ecosystem modeling in an effort to test multiple factors on the loss of marine biodiversity. Limitations of the study included the lack of the frequency of biodiversity data, absence of socio-economic variables of fishery implementation, and exclusion of higher trophic levels such as marine mammal and seabirds. Future research should use of continuous data acquisition technologies, multi-taxon assessments, and examination of additional environmental drivers to better understand and manage ecosystem responses.

VI. Conclusion

This study reveals that marine biodiversity is being lost at ecologically significant rates across both the Indo-Pacific Warm Pool and Arabian Gulf due to synergistic interaction between climate change and overfishing, with rates 2.8-fold greater than climate alone. A 34.6% loss of reef fish species diversity, 47.2% decline of standardized CPUE, 33.4% increase in predator methylmercury concentrations and consistently lowering trophic levels representing a trophic downgrading were observed between the years 2000 and 2023. GAMM analysis confirmed a significant interaction between sea surface temperature anomalies and fishing mortality as the major predictor of species loss and additive effects of ocean acidification to reduce functional diversity, while scenario analysis indicates that only integrated management of strong greenhouse gas emission reductions paired with an 40% fishing mortality reduction will achieve a net loss in biodiversity by 2060, highlighting that solely dealing with climate or fishery policy separately will fail to slow further degradation. This has a significant bearing on the structure and governance of marine protected area networks, that are designed to be climate smart and ecologically connected, and can only deliver conservation outcomes if adequately resourced with management capacity for governance and compliance. Areas for future work include robust, continuous monitoring systems for biodiversity using eDNA and autonomous vehicles, explicit modeling of multi-stressor scenarios to include plastic pollution

and eutrophication, explicit modeling of socio-economic and equity issues associated with conservation costs and benefits for coastal communities, modeling trophic cascades across entire food webs to include megafauna and valuing ecosystem services under varying management regimes for input into decision making processes, and strong political commitment to address overfishing simultaneously with greenhouse gas emissions.

Declarations

Conflict of Interest: The authors declare no conflict of interest, financial or otherwise, that could have influenced the design, conduct, reporting, or interpretation of the research presented in this manuscript.

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Dataset Description: The datasets analysed in this study are derived from publicly available repositories including NASA MODIS-Aqua, NOAA World Ocean Database, FAO FishStatJ, and the Sea Around Us project; processed data and model code are available from the corresponding author upon reasonable request.

References

- [1] Sumaila, U. R., & Tai, T. C. (2020). End overfishing and increase the resilience of the ocean to climate change. *Frontiers in Marine Science*, 7, 523. <https://doi.org/10.3389/fmars.2020.00523>
- [2] Wang, B., Hua, L., Mei, H., Wu, X., Kang, Y., & Zhao, N. (2024). Impact of climate change on the dynamic processes of marine environment and feedback mechanisms: an overview. *Archives of computational methods in engineering*, 31(6), 3377-3408. <https://doi.org/10.1007/s11831-024-10072-z>
- [3] Schartup, A. T., Thackray, C. P., Qureshi, A., Dassuncao, C., Gillespie, K., Hanke, A., & Sunderland, E. M. (2019). Climate change and overfishing increase neurotoxicant in marine predators. *Nature*, 572(7771), 648-650. <https://doi.org/10.1038/s41586-019-1468-9>
- [4] Craig, R. K. (2012). Marine biodiversity, climate change, and governance of the oceans. *Diversity*, 4(2), 224-238. <https://doi.org/10.3390/d4020224>
- [5] Sumaila, U. R., de Fontaubert, C., & Palomares, M. L. D. (2023). How overfishing handicaps resilience of marine resources under climate change. *Frontiers in Marine Science*, 10, 1250449. <https://doi.org/10.3389/fmars.2023.1250449>
- [6] Wabnitz, C. C., Lam, V. W., Reygondeau, G., Teh, L. C., Al-Abdulrazzak, D., Khalfallah, M., ... & Cheung, W. W. (2018). Climate change impacts on marine biodiversity, fisheries and society in the Arabian Gulf. *PloS one*, 13(5), e0194537. <https://doi.org/10.1371/journal.pone.0194537>
- [7] Rice, J. C., & Garcia, S. M. (2011). Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues. *ICES Journal of Marine Science*, 68(6), 1343-1353. <https://doi.org/10.1093/icesjms/fsr041>
- [8] Duarte, C. M. (2014). Global change and the future ocean: a grand challenge for marine sciences. *Frontiers in Marine Science*, 1, 63. <https://doi.org/10.3389/fmars.2014.00063>
- [9] Issifu, I., Alava, J. J., Lam, V. W., & Sumaila, U. R. (2022). Impact of ocean warming, overfishing and mercury on European fisheries: A risk assessment and policy solution framework. *Frontiers in Marine Science*, 8, 770805. <https://doi.org/10.3389/fmars.2021.770805>
- [10] Marques, L. (2020). Collapse of biodiversity in the aquatic environment. In *Capitalism and environmental collapse* (pp. 275-301). Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-47527-7_11
- [11] Green, A. L., Fernandes, L., Almany, G., Abesamis, R., McLeod, E., Aliño, P. M., ... & Pressey, R. L. (2014). Designing marine reserves for fisheries management, biodiversity conservation, and climate change adaptation. *Coastal Management*, 42(2), 143-159. <https://doi.org/10.1080/08920753.2014.877763>

- [12] Perry, R. I., Cury, P., Brander, K., Jennings, S., Möllmann, C., & Planque, B. (2010). Sensitivity of marine systems to climate and fishing: concepts, issues and management responses. *Journal of Marine Systems*, 79(3-4), 427-435. <https://doi.org/10.1016/j.jmarsys.2008.12.017>
- [13] Hutchings, J. A., Cote, I. M., Dodson, J. J., Fleming, I. A., Jennings, S., Mantua, N. J., ... & Weaver, A. J. (2012). Climate change, fisheries, and aquaculture: trends and consequences for Canadian marine biodiversity. *Environmental Reviews*, 20(4), 220-311. <https://doi.org/10.1139/a2012-011>
- [14] Link, J. S. (2021). Evidence of ecosystem overfishing in US large marine ecosystems. *ICES Journal of Marine Science*, 78(9), 3176-3201. <https://doi.org/10.1093/icesjms/fsab185>
- [15] Imoobe, T. O., Isibor, P. O., Agbontaen, D. O., & Akinduti, P. A. (2024). Habitat restoration strategies for arctic marine environments. In *Arctic Marine Ecotoxicology: Climate Change, Pollutants, and Their Far-Reaching Effects* (pp. 437-451). Cham: Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-73584-4_21
- [16] Arabi, M., Mechkirrou, L., El Malki, M., Alaoui, K., Chaieb, A., Maaroufi, F., & Karmich, S. (2024). Overview of ecological dynamics in Morocco–Biodiversity, water scarcity, climate change, anthropogenic pressures, and energy resources–Navigating towards ecosolutions and sustainable development. In *E3S Web of Conferences* (Vol. 527, p. 01001). EDP Sciences. <https://doi.org/10.1051/e3sconf/202452701001>
- [17] Rajan.C. (2025). Climate-Resilient Aquaculture: Adaptive Strategies for Sustainable Production under Changing Ocean Conditions. *National Journal of Smart Fisheries and Aquaculture Innovation*, 2(2), 64-71.