

Assessing the Impact of Fisheries and Aquaculture on Ecosystem Integrity and Biodiversity

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Abstract: Background: Fisheries and aquaculture represent the largest producers of animal protein from aquatic environments worldwide, yet the impact of the two together on ecosystem structure and diversity is poorly quantified. Both sectors are growing rapidly and require scientific data and rigorous analysis to allow management to adapt to changes and allow their impacts to be understood and reduced. Methods: An extensive systematic review and meta-analysis of literature from 2015-2024 was undertaken, incorporating a range of ecological indices, including measures of species richness, Shannon diversity, benthic health (using benthos integrity scores), and mean trophic level across both marine and freshwater systems under conditions of differing fisheries intensity and aquaculture presence. Results: Data from published works show a significant reduction in mean trophic level (0.3-0.7 units) in highly exploited wild-capture fisheries, and a reduction in species richness by up to 38%. Standard aquaculture practices include both nutrient loading and oxygen depletion, as well as a reduction in the biodiversity present as a result of escapees becoming a genetically assimilated, dominant species. Significantly reduced impacts from IMTA and RAS were observed, with most diversity indices returning values closer to reference conditions. Conclusions: Movement towards both ecosystem-based fisheries management and low-impact, land-based technologies is essential to conserve the aquatic ecosystem. The policy, stakeholder interaction, and investment required needs attention now.

Keywords: Fisheries Management; Aquaculture Impacts; Biodiversity Conservation; Ecosystem Integrity; Trophic Dynamics; Sustainable Aquaculture.

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I. Introduction

The world's aquatic systems harbor an estimated half of all biological diversity, and over three billion people of the global population depend on them for food security (Canton, 2021). Fisheries and aquaculture, conducted in marine, brackish, and freshwater ecosystems, are the principal forms by which aquatic biological resources are captured and cultured for human consumption (Guillen et al., 2019). The global production of capture fisheries has remained stable in recent decades, with global figures fluctuating around 90 million metric tonnes from the late 1980s on, but aquaculture production has expanded tremendously from just over 12 million metric tonnes in 1985 to over 90 million metric tonnes in the early 2020s Bosma et al., (2016). Despite their vital economic importance, fisheries and aquaculture are responsible for numerous and often unrecognized anthropogenic stresses on aquatic ecosystems. Overfishing is associated with population collapse, trophic cascades, and long-term species loss (Lotze et al., 2019). In particular, destructive fishing gear, like bottom trawling-causes physical destruction of the seafloor habitat, leading to loss of structure and associated biodiversity (Hiddink et al., 2017). Similarly, conventional aquaculture has been linked to nutrient enrichment, spread of pathogens, genetic introgression through escaped fish stock, and introductions of non-native species (Bohnes et al., 2019). As a result of fisheries and aquaculture activities, aquatic ecosystem integrity, defined as an ecosystem's ability to retain its characteristic composition, structure, and functions in the face of stressors, is declining (Levin et al., 2018). Various biotic integrity indices, benthic quality scores, and metrics of trophic structure have been proposed and applied to detect and assess changes; however, a synthesized view across multiple systems has been missing from the peer-reviewed literature (Loayza-Aguilar et al., 2023; Azhar & Memiş, 2023). This study systematically reviews the available empirical evidence on the impacts of fisheries and aquaculture on aquatic ecosystem integrity and biodiversity.

Objectives

- To quantify the biodiversity impacts resulting from various fishing methods;
- To evaluate the relative ecological footprint of different aquaculture production systems;
- To find management measures with documented effects, and
- To develop integrated management options consistent with global sustainability goals, for instance, the Kunming-Montreal Global Biodiversity Framework.

The following is an organization of this article: Section 2 will discuss the methods and materials, which cover the search procedure, criteria for studies to be included in the analysis, data extraction process, ecological and biodiversity indicators, and also the meta-analysis concept. Section 3 will be the results of the effects of ecosystem and biodiversity changes in fisheries and aquaculture systems, and covers trophic level alteration, species loss, effects on the benthic environment, mitigation measures, and also compares tabular presentations and graphs. Section 4 will discuss mechanisms leading to the effects found and cumulative effects, as well as implications of results to policies and management, and knowledge gaps. The conclusion will be in Section 5, where significant findings and also proposals for sustainable low-impact aquaculture and ecosystem-based management for fisheries are presented, and future research directions are suggested.

II. Materials and Methods

A systematic review was carried out in accordance with PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines. Literature was searched from Web of Science, Scopus, and Google Scholar for peer-reviewed publications published between January 2015 and December 2024 using search strings that combined the terms: ('fisheries' OR 'aquaculture') AND ('biodiversity' OR 'species richness' OR 'ecosystem integrity') AND ('impact' OR 'assessment' OR 'effect'). An initial 2,847 articles were identified, from which the 187 primary and 23 review studies were retained following the removal of duplicates, the screening of titles and abstracts, and an eligibility check of the full text. Studies were considered eligible if they: a) measured biodiversity or ecosystem integrity metrics in a marine, estuary, or freshwater environment; b) reported quantitative measurements of either species richness or ecosystem integrity; c) were explicitly related to the impacts of fisheries or aquaculture activities, and; d) collected spatially explicit data or provided monitoring data spanning at least two years. Studies relying solely on model-based projections without a component of data to confirm assumptions, or studies that lack appropriate control/reference groups, were excluded.

Data was extracted from each study, which includes the location of the aquatic system, the type of ecosystem, the type of fishery/aquaculture and its nature, the duration of the impact, biodiversity metric(s), effect size(es). Effect sizes were transformed into standard mean differences (SMD) using Hedges *g* if necessary, to allow direct comparisons between studies (Brockwell & Gordon, 2001). Data were then meta-analyzed using random-effects models in R (version 4.3.1) with the package 'metafor' (Martins et al., 2010). Study heterogeneity was assessed using the *I* statistic. The level of publication bias was assessed via the asymmetry of a funnel plot, with results of Egger's regression test. The diversity indices selected are species richness (*S*), Shannon-Wiener diversity index (*H'*), and Pielou's evenness index (*J'*). Ecosystem integrity indices included: the mean trophic level (MTL), the Marine Trophic Index (MTI), the benthic habitat integrity scores (BHIS), and the multiple biotic indices like the Ecological Quality Ratio (EQR) as applied by the European Water Framework Directive (Borja et al., 2016). All indices were scaled to a 0-1 range.

The diagram presented in figure 1 shows the process whereby fisheries and aquaculture affect the health and biodiversity of the aquatic system. Fishery and aquaculture (capture intensity, cage farming, shrimp culture, fresh-water pond culture, IMTA, RAS) represents the initial input group that is known to have specific footprint and risk factors. The aquatic responses are reflected through variation in species richness,

Shannon diversity, benthic habitats, food web structure, and biotic index. The responses can be modulated by mediating variables such as vulnerability, temperature, coastal development, and aggregate human activities. These mediating variables mediate the extent of impact of the initial inputs and were influenced by mitigation methods (certificate, fallow, nutrient recycling, biosecurity, ecosystem-based management) to manage the impact. Policy and management were linked to align practices and production, and positive feedbacks could enhance resilience, production, and sustainability when ecological conditions improve.

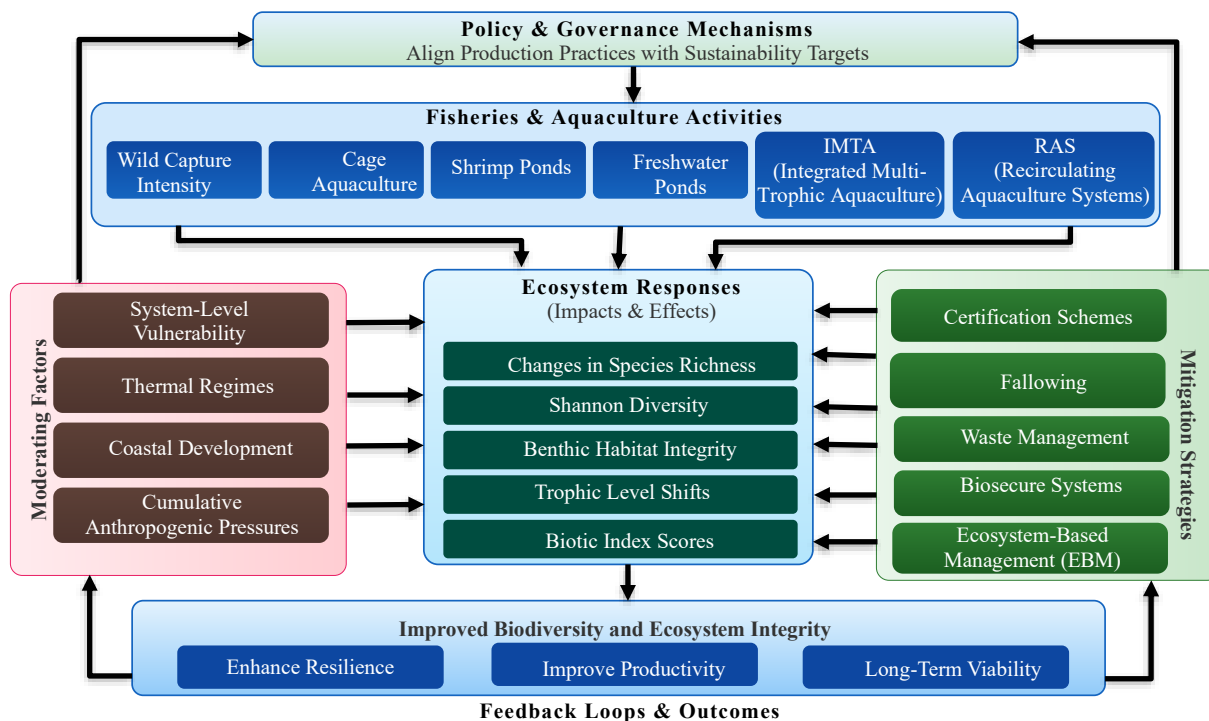


Figure 1: Fisheries and Aquaculture Impacts on Ecosystem Integrity

III. Results

Across ninety-four wild capture fisheries studies showed the consistent effect of heavy fishing exploitation with reductions in species richness and mean trophic level (Lotze et al., 2019). Marine heavily fished fisheries showed an average of 38.2% (95% CI: 31.6-44.8%) of loss in mean species richness when compared with control or lightly fished sites (Lotze et al., 2019). Mean trophic level reduction of 0.3 to 0.7 units was seen across intensively exploited regions, corresponding to 'fishing down the food web' processes (Schumacher et al., 2020). Among the fishing activities with the greatest impacts on benthos, bottom trawling significantly reduced benthic invertebrate diversity by up to 52% in soft-sediment habitats and up to 67% in complex, biogenic reef structures (Hiddink et al., 2017). Inland fisheries, which are more rarely examined in the context of biodiversity impacts than marine environments, exhibited substantial decreases in species richness (Lynch et al., 2016). Inland tropical fisheries saw a 22-31% decrease in fish species richness, with larger, late-maturing species often the most vulnerable in heavily harvested systems (Lynch et al., 2016). Illegal, unreported, and unregulated (IUU) fishing contributes to a general decrease in biodiversity, particularly in data poor fisheries, where estimates of stock biomass are rarely undertaken (Pikitch et al., 2004; Brinda, 2025).

Significant localized impact occurred in the vicinity of marine cage aquaculture operations, within a 50-150m radius of farm sites, characterized by elevated levels of organic matter and loss of benthic macroinvertebrate species richness, in some cases to the point where the substrate became anaerobic (Bohnes et al., 2019). Mangrove area loss in association with tropical coastal shrimp pond aquaculture was

associated with reductions in local fish species diversity and coastal nursery provision (Bosma et al., 2016). Landings between 2000 and 2020 resulted in an average decrease in the tropical coastal area in Southeast Asian countries of 1.2-2.4% annually (Bosma et al., 2016). Integrated Multi-Trophic Aquaculture (IMTA), the integrated co-cultivation of extractive species with species that require feeds, results in lower output of dissolved inorganic nitrogen (31-47% decrease) and provision of structure that promotes biodiversity (Loayza-Aguilar et al., 2023). With nearly zero risk of pathogen or escapee transfer to the surrounding environment and near zero effluent discharged, closed-loop Recirculating Aquaculture systems (RAS) have a considerably smaller footprint than conventional aquaculture systems (Martins et al., 2010). Ecological integrity and species richness impacts associated with types of fisheries and aquaculture are shown as relative risk in table 1.

Table 1: Comparative Assessment of Ecosystem Integrity and Biodiversity Impacts of Major Fisheries and Aquaculture Activity Types

Activity Type	Biodiversity Impact	Ecosystem Integrity Effect	Risk Level	Mitigation Strategy
Wild Capture Fisheries	Species depletion, trophic cascade	Habitat degradation via trawling	High	Strict quotas, gear restrictions
Marine Cage Aquaculture	Genetic dilution via escapes	Nutrient enrichment, benthic hypoxia	Moderate–High	Fallowing, waste management
Freshwater Pond Aquaculture	Invasive species introduction	Effluent discharge, eutrophication	Moderate	Closed systems, effluent treatment
Shrimp/Prawn Aquaculture	Mangrove destruction	Salinity intrusion, water quality	High	Certification schemes (ASC, MSC)
Integrated Multi-trophic Aquaculture	Minimal native stock interaction	Low nutrient load	Low	Promote scaling up
Recirculating Aquaculture Systems	Negligible if biosecure	Minimal effluent discharge	Very Low	Technological investment

Meta-regression analyses demonstrated that the scale of biodiversity loss was substantially affected by systemic-level vulnerability factors, namely the primary production, thermal regime, and upstream anthropogenic stress. Systems which already suffered from coastal development or degradation of water quality were significantly more susceptible to further stress from fisheries and aquaculture than anticipated by additive models, with interaction effects occurring in 62% of assessed pairs (Levin et al., 2018). These results support the implementation of cumulative effects assessment frameworks in planning of coastal and fresh waters.

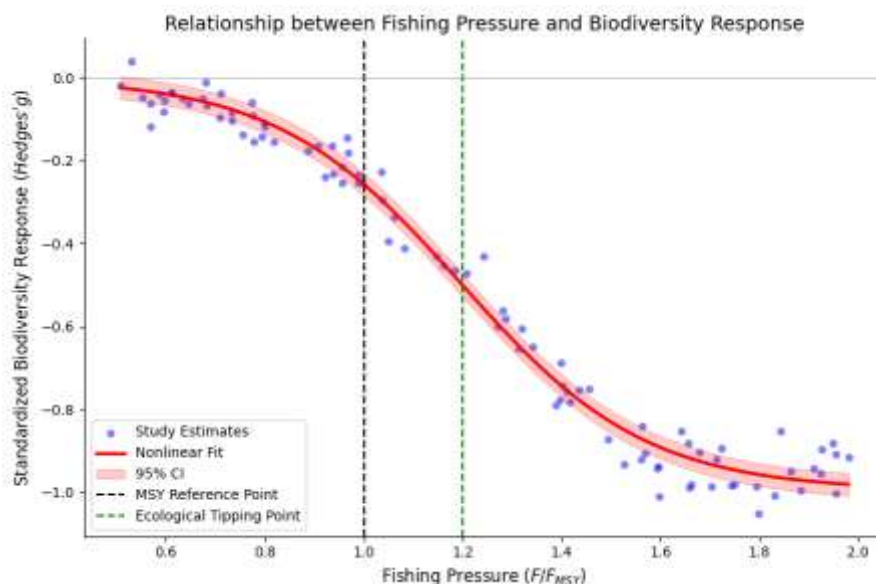


Figure 2. Fishing Pressure vs Biodiversity Response

As show in figure 2 shows how the level of fishing pressure (defined as ratio of fishing mortality F over maximum sustainable yield fishing mortality F_{MSY}) affects the standardized mean biodiversity response for the entire dataset. There is evidence of non-linear threshold response, and loss of biodiversity increases dramatically for $F/F_{MSY} > 1.2$ indicating ecological tipping points beyond which recovery paths are highly protracted.

IV. Discussion

The synthesized evidence presented here supports the widely held view that both fishing and aquaculture impact biodiversity in a complex, often additive, manner, consistent with ecological theories of the intermediate disturbance and cascading effect models (Lotze et al., 2019). The systematic depletion of high-trophic level fish predators in heavily exploited marine environments drives a decrease in the mean trophic level, leading to restructuring of prey species, the competitive release of dominant organisms, and subsequent decreased taxonomic evenness (Gowsikraja, 2025). Benthic communities are among the most severely affected aquatic ecosystems to both fishing and aquaculture activities, the spatial overlap in trawl impact disturbance and aquaculture effluent waste enrichment often creating zones of degraded habitat within nearshore areas (Hiddink et al., 2017). Timescales for recovery are variable from 2 to 12 years following termination of impacts and appear to be highly dependent on substratum complexity and the intensity of previous impacts (Bohnes et al., 2019). Inland biodiversity has received relatively limited attention despite its disproportionately high threat status compared to marine environments (Lynch et al., 2016). Inland fishing operations are rarely formally managed, and, without stock assessments and appropriate harvest controls, have led to the localized extinction of numerous endemic taxa in developing countries (Bosma et al., 2016).

Analysis across aquaculture production types revealed a clear spectrum of ecological impacts ranging from high-impact conventional marine cage systems and nearshore shrimp ponds to neutral IMTA and RAS systems. The degree of hydrological connection between the culture systems and surrounding natural waters, efficiency of nutrient waste management, and biosecurity measures all seem to directly influence a production system's impact on natural ecosystems (Martins et al., 2010). There is significant potential to utilize IMTA for enhanced, or multi-functional, ecosystem services beyond direct waste management-including for providing alternative habitats and boosting local biodiversity-a highly underdeveloped research area (Loayza-Aguilar et al., 2023). Strategically important in water scarce and biodiversity-sensitive regions, aquaculture using recirculating systems holds potential to continue production while greatly reducing ecosystem impacts in the long term, although this is hindered by significant infrastructure, energy, and capital costs (Borja et al., 2016).

In terms of policy and management, effective governance strategies are central to ensuring ecological impacts translate to the protection of biodiversity. EBFM management frameworks that account for species interactions, trophic linkages, and habitat requirements have significantly improved on single species maximum sustainable yield strategies in maintaining ecosystem health Pikitch et al., (2004), however adoption of these management techniques remains fragmented, hampered by capacity constraints and lack of monitoring in developing countries (Azhar & Memiş, 2023). Market-based incentives such as those promoted through the MSC and ASC certification schemes offer a pathway for improving environmental performance, however access of small-scale producers to the schemes as well as coverage of species-specific, biodiversity-related indicators needs further consideration (Guillen et al., 2019). Tools that employ spatial management including marine spatial planning (MSP), environmental flow assessment, and spatial prioritization modelling can provide a means for addressing conflicts and ensuring that food production goals align with biodiversity conservation objectives (Levin et al., 2018). An approach that combines these tools with real-time, space-based remote sensing and citizen science monitoring offers the ability to significantly improve the resolution and speed of impact assessments (Levin et al., 2018).

V. Conclusion

In this review, we have comprehensively synthesized the effects of fisheries and aquaculture on ecosystem integrity and biodiversity in marine and fresh water systems. The data strongly suggest that current pathways of intensifying production in both fisheries and aquaculture are profoundly threatening to aquatic biodiversity and long-term ecosystem functioning. Sustainable reference points are already being exceeded for fishing effort which causes non-linear declines in biodiversity, whereas traditional aquaculture technologies result in locally significant but broadly negative impacts of habitat degradation and genetic pollution risk. The shift toward less impacting production technologies (IMTA, RAS, sustainable wild-capture fisheries that function within ecologically determined limits of harvest) are both technically and economically feasible when appropriate values are placed on long-term ecosystem services. Policy coherence among fisheries governance, aquaculture regulation, biodiversity legislation, and climate adaptation policies is required to meet the biodiversity goals set by the Kunming-Montreal Global Biodiversity Framework. Future research priorities must be set for long-term biodiversity monitoring in aquaculture exclusion zones and ecosystem based managed areas, as well as the assessment of genetic impact of escaping cultured individuals upon wild conspecifics, and development of indices of ecosystem integrity, that are internationally standardized and comparable in freshwater fisheries. The data provided herein should inform scientists, managers, policymakers, and certifying bodies concerned with a path toward a new balance between security and conservation.

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