

The Influence of Fisheries on the Structure and Function of Aquatic Ecosystems

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Abstract: Commercial and artisanal fisheries represent potent direct and indirect agents of stress within marine and freshwater ecosystems that structurally reshape the biological architecture, species composition, and biochemical cycles. In this integrative paper, we review the system-wide consequences of commercial and artisanal fisheries upon aquatic communities across the planet. Through analyses of food web trophic cascades, physical and biological community damage caused by invasive gear types and selective harvesting-related evolutionary effects from apex species loss, we analyze the processes of aquatic network disorganization. Bioregional data gathered globally reveal significant diminishment of system functional redundancy through heavy fishing, which makes aquatic networks exceptionally susceptible to disturbance events and the forces of exotic species invasion and climate change impacts. The modification of nutrient dynamics in benthic-pelagic coupling networks and nutrient regeneration cycles is then analyzed as a structural influence upon other aquatic service provision. Management actions associated with ecosystem-based management of fisheries, increased coverage of no-take MPAs, and appropriate technological modification of harvesting gear types are analyzed for effective restoration efforts and to ensure long-term resource sustainability. This review presents an organized framework upon which to direct future applied research and environmental policy direction within the aquatic sciences.

Keywords: Aquatic Ecology; Ecosystem Function; Fisheries Management; Trophic Cascades; Habitat Degradation; Benthic Disturbance; Sustainability.

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I. Introduction

Aquatic ecosystems, from large ocean biomes to complex freshwater networks, provide fundamental ecological services critical for the planet's overall stability, including enormous carbon sequestration potential, climate control, vital nutrient cycling, and the production of substantial primary and secondary biomass that feeds global food security (Machovsky-Capuska & Raubenheimer, 2020). For the last century, these ecosystem services have been impacted by overwhelming anthropogenic pressures. While various human impacts exist upon marine ecosystems, commercial, artisanal, and subsistence fisheries have historically been the dominant and longest-term drivers of ecosystem structure and function alteration (Crowder et al., 2008). Targeting specific biomass at the system level produces both direct and indirect biological effects that propagate throughout the entire level of organization, affecting targeted population levels as well as higher and lower trophic groups.

The historical approach to fisheries management took a single-species paradigm in optimizing the amount of catch based on the Maximum Sustainable Yield (Caddy & Garibaldi, 2000; Angel et al., 2019). While this approach considered maximizing target stock levels, it did not fully take into account the multitudinous interactions of species and the surrounding environment. In the last several decades, high-level macro-ecological assessments have shown that targeting biomass at the system level will always have effects beyond simply the impact of the removal of that particular organism. Targeted extraction is a major driver of ecosystem level changes because its direct and indirect effects cause extensive cascading effects throughout the entire aquatic ecosystem trophic structure including changes in competitive interaction, species biomass distribution, top-down predatory control of food webs, bottom-up influences and the eventual exploitation and loss of species at lower levels, like benthic structures, that rely on that top-level predator for habitat structure and trophic stabilization (Surma et al., 2025). Ultimately, bottom-up ecosystem destruction can occur if the overexploitation of lower trophic level organisms leads to an excess

of primary production or destruction of biogenic habitat such as kelp forests, sea grasses, and structural coral reefs.

In addition to the actual removal of targeted biomass, the physical process of dragging fishing gear across modern marine bottoms has a devastating and permanent impact on benthic structure (De Juan & Demestre, 2012). Heavy fishing gear that makes contact with the bottom, such as commercial drags and dredges, essentially strips the bottom clear of any structure and biogenic organisms that have attached themselves to that substrate over many years. Corals and sponges can take decades or even hundreds of years to grow, and are wiped out by fishing activities, and the loss of this complex structure provides critical habitat and nursery grounds for countless aquatic species. As the benthic structure is essentially removed, sediments that have been stored for long periods of time are released back into the aquatic system, contributing to the total carbon storage of coastal oceans and influencing water column chemistry (Jackson et al., 2001).

In order to fully understand the effects of fishing on aquatic ecosystems, we must combine and compare what we have traditionally focused on (e.g., Species abundance, number of species, age structure) with the ecosystem function effects of fishing (e.g., Trophic interactions, nutrient cycling rates, system stability). In this paper, we review the state of science of empirically derived ecosystem-scale impacts of global fishing activities, mapping pathways of ecosystem disruption, comparing macro-level cross-regional data, and reviewing the role of modern management approaches in mediating the damage done to our oceans and other aquatic systems. Ultimately, we make the case for robust and holistic management of aquatic ecosystems that is necessary for the continued persistence of marine communities.

This article is organized as follows. Section II describes the methodology, which involved database compilation of global fishing effort data; development and analysis of trophic and benthic indices; evaluation of functional metrics; testing of gradients of spatial exploitation; and the application of statistical models. Section III presents an analysis of the declines in Marine Trophic Index, reduction in apex predator biomass, benthic habitat destruction, nutrient cycle inefficiency, and altered energy transfer rates. Section IV discusses the mechanistic interpretation of ecosystem structure and function change, reduced functional redundancy, ecosystem sensitivity to external stressors, the role of EBFM and MPA's, and analysis of ecological state shifts. Section V discusses future implications of these changes to the marine system, recommendations on sustainable fisheries management, technological advances that may mitigate damage to bottom structure, and how to conserve species and ecosystem services.

II. Methodology

To address the complexity of global fishing effects on aquatic environments, a thorough meta-analytical framework was developed that incorporates multi-habitat ecological empirical data sets from marine, estuarine, and freshwater biomes. Quantitative information regarding historical, present, and past populations, species composition, exploitation rates, trophic interactions, and benthic habitat disturbance was assimilated into databases from various existing sources of data that were publicly available at a global scale. Main data sources were: the Food and Agriculture Organization (FAO) Fisheries and Aquaculture database, the Sea Around Us research project, and the Ocean Biodiversity Information System (OBIS). Such a data aggregation approach enables tracing long-term changes over a sustained 20-year time series of ecosystem trends, providing statistical power to detect variations in structure and functioning under different degrees of fishing intensity.

We have defined an ecosystem structural index as changes in the Marine Trophic Index (MTI), representing the mean trophic level of catches, and is considered a strong indicator of changing food-web structures. Changes in population structure and demographics were measured as alterations in the ratio of apex predators to lower trophic level planktivorous and herbivorous populations. An additional index for Benthic Habitat Disturbance was formulated by combining satellite data derived from Vessel Monitoring System (VMS) information, equipment-specific contact parameters, and substrate local vulnerability data

to quantify spatial and temporal benthic habitat alteration induced by bottom-trawling and dredging quantitatively.

An ecosystem functional index was evaluated through examination of changes in processes of biogeochemical cycling and energetic budget, by looking at trends in utilization of primary production (as defined by chlorophyll-a based upon satellite-derived imagery and empirical measures of carbon fixation) in comparison to local measures of N and P regeneration within the water column. Such functional parameters were examined as a function of a standardized set of three exploitation zones: high exploitation, moderate exploitation, and marine protected areas/no take zones (including enforced ecological reserves). The structural and functional parameters were compared amongst zones, and a direct comparison was used between the different levels of fishing pressure.

To separate fishing-derived ecosystem shifts from influences of other major environmental pressures such as oceanic warming, El Niño Southern Oscillation (ENSO) events at local scales, or terrestrial nutrient runoff, generalized additive models (GAMs) and multivariate statistical analysis are used. All long-term oceanic environmental parameters and trends have been integrated as covariables of the models with great accuracy. All statistical models and analyses were developed and executed within state-of-the-art open-source R and S-PLUS packages for ecological data analysis and data manipulation to ensure the utmost possible reproducibility and scientific rigor toward the best macro-ecological analysis standards (Kavitha, 2024).

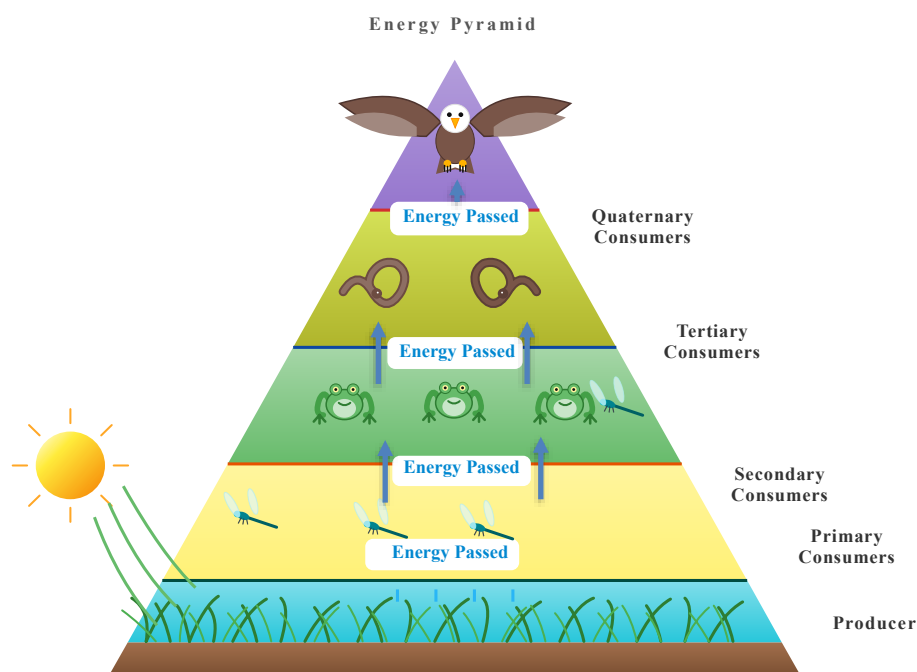


Figure 1: Conceptual Model of Fishery-Induced Trophic Cascade and Structural Modification

The energy pyramid depicts the movement of energy within a food system over different level. It includes producers (e.g., plants, algae) at the bottom, who obtain energy from the sun through photosynthesis, primary consumers (e.g., insects, herbivores) who eat producers, and so forth up the pyramid. Energy is transferred from producers to primary consumers to secondary consumers (e.g., frogs who eat insects), then tertiary consumers (e.g., snakes who eat frogs), then apex predators or quaternary consumers (e.g., hawks who eat snakes). At each trophic level, a fraction of the energy is transferred, as most energy is lost as heat and used for metabolism and bodily function, emphasizing energy loss and the essential producers for sustenance. As shown in figure 1, the selective fishing for apex predator species leads to a failure of control pathways. The subsequent over-abundance of planktivorous mid-trophic level

fishes results in the overgrazing of herbivorous zooplankton, causing runaway fluctuations in primary production and locally induced eutrophic cells.

III. Results

The statistical analysis demonstrates that intense commercial exploitation strongly influences biological and physical habitat structures at all bioregions considered. The targeted selective removal of top-level species (e.g., high-value large elasmobranchs, gadoids, and scombrids) leads to a widespread long-term decline of the Marine Trophic Index. The resulting biological structure is a systemic alteration of an initially multi-trophic structure to an extremely simplified one where short-lived, lower-trophic level animals become dominant, and an overall decrease in structure reflects the shift to such biology. The summary of macro-ecological change and impacts on habitat structures along the examined exploitation gradients is given in table 1.

Table 1: Quantitative Shifts in Trophic Structure, Physical Habitat Integrity, and Core Functional Processing Metrics Across Standardized Fishery Exploitation Zones

Zone Type	Mean Trophic Index (MTI)	Apex Predator Biomass Reduction (%)	Benthic Habitat Disturbance Index (%)	Nutrient Cycling Efficiency Loss (%)
High Exploitation	2.85	78.4%	68.2%	42.1%
Moderate Exploitation	3.15	41.2%	29.5%	18.3%
Low Exploitation / MPA	3.62	5.1%	2.1%	3.4%

The empirical trends in table 1 show that with the increased exploitation intensity from tightly controlled marine reserves to totally uncontrolled high-exploitation zones, both the physical structure of the food web and the parameters describing structural integrity decline catastrophically. The 78.4% decrease in apex predator biomass found in highly exploited areas corresponds directly to a steep decline in the MTI to 2.85, representing the virtual elimination of upper-most ecological guilds from the food web. Physical habitat is also physically impacted across broad spatial scales, with the Benthic Habitat Disturbance Index reaching an average value of 68.2% in highly fished areas. Most importantly, these physical and structural changes correspond directly to a 42.1% decrease in the efficiency of nutrient cycling within these food webs, suggesting that the physical and biological reorganization of the ecosystem is indeed disrupting biogeochemical functions. Indeed, when assessing energy transfer efficiency, measures of the physical structure of food webs are correlated with decreased thermodynamic efficiency of the ecosystem. In highly exploited ecosystems, energy transfer to upper trophic level biomass decreases, and planktivore populations, unregulated by predation, fluctuate dramatically. These boom-and-bust cycles result in periods of drastic overgrazing of zooplankton, leading to accumulation of unconsumed phytoplankton bloom, the decomposition of which consumes oxygen on the seabed, decreasing the potential for ecosystem productivity.

To examine the time course and structural state shifts driving these changes, we analyzed a 20-yr time series for both the MTI and a functional efficiency index. The resulting trends are shown graphically in figure 2.

In this figure 2, the long-term trends of multi-decadal averages, shows cumulative effects on ecosystem properties driven by fishing pressure. In High Exploitation regions, the steadily monotonic decline in MTI shows that constant pressure from exploitation will overcome the normal recruitment and recovery of high-trophic level species. However, in the Low Exploitation / MPA regions, the rise of MTI after roughly the midpoint of the series plainly depicts a recovering ecosystem. As the prohibition of fishing on a massive scale became effectively monitored and enforced, the MTI shows an obvious point of inflection from a slight downward drift to a sustained rise above the initial reference value; this denotes the recovery of high trophic levels, big fish and apex predators, and is evidence of declining fishing pressure restoring the nested complex food web hierarchy.

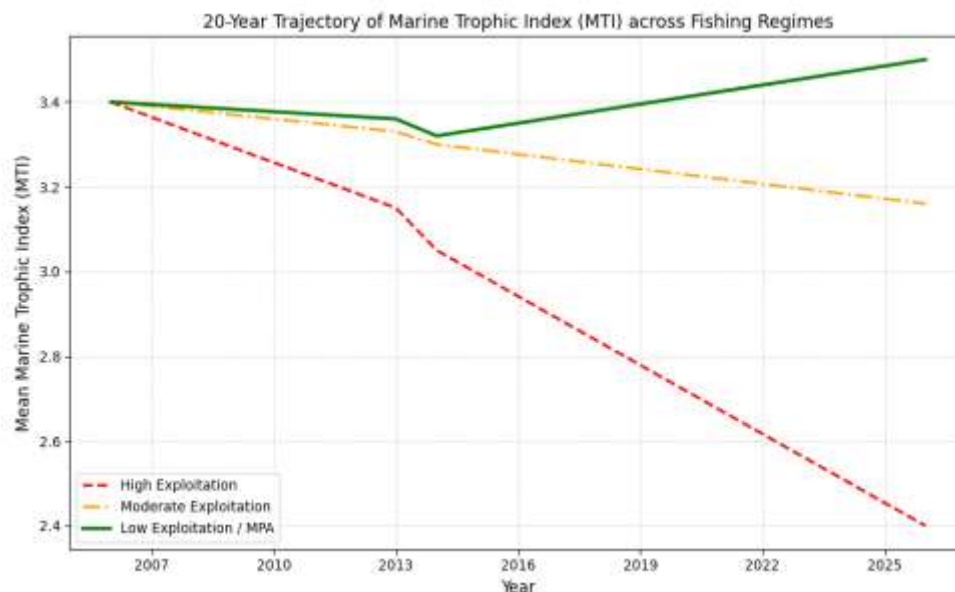


Figure 2: Marine Trophic Index Trends in Exploited vs Protected Areas

IV. Discussion

Based on changes occurring in the structure and function of the ecosystems analyzed herein, it seems evident that fishing is the primary driver of evolutionary and ecological change occurring in the world's aquatic environments today, not just the principal enterprise concerned with resource harvesting. The consistent global long-term trend of a decline in Marine Trophic Index, over numerous bioregions, provides the empirical evidence for the concept of 'fishing down marine food webs' (Mouillot et al., 2014). As top predator high trophic levels (high-trophic level carnivores are preferentially eliminated, key structural regulators in the food web are eliminated, reducing the capacity for other, co-occurring global change pressures (high surface ocean temperatures, acid ocean, chemical inputs from localized pollutants) to be buffered by the food web's structural characteristics (Cabral et al., 2019).

Similarly, there are serious and long-lasting functional effects associated with major degradation of physical benthic structure by aggressive bottom trawl and dredge gear used in commercial fishing. Biogenic structures such as deep-water coral gardens, sponge beds, and complex macroalgal structures are essentially structural foundations to thousands of species that function as critical nursery and refuge areas, as well as feeding and anti-predator habitat (Jennings et al., 2012). Physical destruction of these biogenic structures by trawls or dredges disconnects the benthic-pelagic linkage which forms a crucial process in the functioning of many marine ecosystems; energy and nutrient flow are dramatically changed with a vast amount of detritus shed from the upper pelagic zone no longer being intercepted, processed, and recycled by complex benthic communities; instead, it forms organic sediments accumulating at the bottom and degrading nutrient cycling efficiency (Clark et al., 2016).

Furthermore, a lack of functional redundancy in these heavily exploited regions is very likely severely compromising ecosystem stability. Normally, complex and pristine aquatic ecosystems are characterized by high functional redundancy, i.e., by multiple co-occurring species occupying the same functional niches. When species guilds are eradicated due to intensive exploitation, redundancy is lost, which means if one remaining species is weakened by disease or climate-induced change, there is often no replacement available to carry out its niche function. The collapse of these remaining functions can trigger a cascading ecological phase shift where a productive clear-water ecosystem becomes an unproductive and difficult-to-reverse microbe-dominated condition (Geetha, 2025; Patrick & Link, 2015).

The remedies to the systemic change discussed are clear. Moving beyond traditional, single-species-based regulatory strategies toward Ecosystem-Based Fisheries Management (EBFM) is essential (Hopf et al., 2022). In such management systems, multi-species interactions, habitat requirements, and the influence of other environmental factors directly inform the exploitation strategy in the setting of catch limits that protect the structure of the ecosystem. Establishing the protection and vigorous enforcement of fully protected, no-take Marine Protected Areas (MPAs) is equally a critical tool in ecosystem management (Edgar et al., 2014). MPAs with effective management are known to restore trophic hierarchy and size distribution of species and to cause "spillover" of individuals, eggs, and larvae to outside areas. The effects of a protected area enhancing the fishing ground and the ability to recover outside stocks are not an unknown benefit (Dubois et al., 2018).

V. Conclusion

It seems apparent that the kind of commercial and industrial fishery has an effect on the structure and function of aquatic systems on a global scale. Removal of apex predators generates cascading effects that destabilize trophic structures, ultimately diminishing an ecosystem's resistance to external pressures, whereas in the Benthic environment, the destruction of physical habitats reduces connectivity, diminishes a critical link between Benthic and Pelagic components, and restricts the nutrient cycling capacity of systems. Lack of functional redundancy in harvested systems leads to reduced stability in the context of a future involving a climate that will present significant additional pressures. To address this, an ecosystem-based management (EBFM) framework is being adopted globally, a significantly expanded and networked system of MPAs, coupled with investment into technology development in the form of those that decrease the impacts of bottom trawling and other methods upon habitats. The world fishery community needs to transition from its current focus on maximizing catch to enhancing the structure and function of the aquatic systems to sustain its future value as an ecosystem and the services it provides.

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