Ecological Change in the Oceans and the Role of Fisheries

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When I took a course with Elisabeth Mann Borgese in 1999, she reminded us that the oceans are constantly changing, both in their outer appearance, and their internal workings. Constant ecological change makes the ocean fascinating to observe and study, but challenging to understand and manage.

Long-term changes are brought about by geological processes such as sediment transport, volcanism, and plate tectonics that affect the very shape of ocean basins and the extent of habitat features such as shallow shelf seas conducive to biological productivity. On intermediate time scales, climate-driven changes in ocean temperature, circulation, and chemistry can have profound ecological effects on the abundance and distribution of marine life forms, and even caused massive extinction events in the past. Over the last few thousand years, however, people have gradually become a dominant agent of change in the oceans. Initially tied to the continents where we evolved, human hunters at least 42,000 years ago started to venture out into the ocean to pursue large fish.¹ Driven by changes in fishing technology, human population size, and global trade, this role has been extending to all ocean basins, and even parts of the deep sea. Over the last two decades, the profound ecological change brought about by human activities has also been studied in detail by the scientific community.

Although human impacts on ocean ecosystems involve many pathways, there is little doubt that fishing—defined here as any extraction of marine animals and plants—is the activity that historically has had the most transformative ecological effects.² Although it is not clear how much marine life has been removed over the entire history of fishing, recent total catches likely

¹ S. O’Connor, R. Ono and C. Clarkson, “Pelagic Fishing at 42,000 Years Before the Present and the Maritime Skills of Modern Humans,” Science 334, no. 6059 (2011): 1117–1121, doi.org/10.1126/science.1207703.
² B. Worm and H.S. Lenihan, “Threats to Marine Ecosystems: Overfishing and Habitat Degradation,” in Marine Community Ecology and Conservation, ed., M.D. Bertness (New York: Sinauer, 2013), 449–476.
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exceed 100 million tonnes each year, when accounting for unreported landings and discards that are not captured by official statistics.³

This intense pressure has caused many species to become rare, or even extirpated at a local scale. For example, an estimated 96% of local extinctions in coastal ecosystems around the world involved fishing and hunting.⁴ Another study of the factors that drive extinction risk today found that exploitation caused a majority of marine species losses (55 percent), followed by habitat loss (37 percent).⁵ Clearly, by targeting certain species of commercial interest, we can eliminate these species from local ecosystems and regional seas, although very few cases of global marine extinctions have so far been documented.

Unfortunately, many fishing methods are unselective, such that a number of species are captured in addition to the intended target species. Bycatch is often thrown back dead at sea, and such total global discards may exceed 10 million tonnes per year.⁶ Consequently, while contemporary fisheries are not usually targeting marine mammals, seabirds, and sea turtles, 20 to 38 percent of these species are threatened, many of them because they end up as bycatch in various fisheries.⁷

The depletion of both target and bycatch species can have a range of secondary effects, depending on how those species are connected in the local food web. Numerous studies have now quantified these ripple effects, such as the unregulated growth of certain prey species, or the decline of predators that were dependent on a fished forage species. Some of these so-called trophic cascades may have even changed plankton species composition at the bottom of the food web, although it is not yet clear how general these effects may be.

Another class of effects arises from the interaction of fishing with seafloor habitats and sedentary species, many of which are affected by bottom-touching trawls and dredges. Biogenic habitats formed by corals, sponges, and other fauna tend to be particularly vulnerable, and often take many years to recover after being impacted by fishing gear. Scientists are now trying to map the distribution of such sensitive habitats in order to protect them from repeated disturbance.

³ D. Pauly and D. Zeller, “Catch Reconstructions Reveal that Global Marine Fisheries Catches are Higher than Reported and Declining,” Nature Communications 7 (2016): 10244, doi.org/10.1038/ncomms10244.
⁴ H.K. Lotze et al., “Depletion, Degradation, and Recovery Potential of Estuaries and Coastal Seas,” Science 312, no. 5781 (2006): 1806–1809, doi.org/10.1126/science.1128035.
⁵ N.K. Dulvy, Y. Sadovy and J.D. Reynolds, “Extinction Vulnerability in Marine Populations,” Fish and Fisheries 4, no. 1 (2003): p. 25–64, doi.org/10.1046/j.1467-2979.2003.00105.x.
⁶ Pauly and Zeller, supra note 3.
⁷ Worm and Lenihan, supra note 2.
When taken together, these various impacts can bring about lasting ecological changes. Heavily fished ecosystems tend to lack many of the larger, slow-growing predators such as sharks and groupers. The density of large predators is often reduced by an order of magnitude or more, and their prey species may dominate the ecosystem, if they are not fished in return. We often find a pattern of serial depletion from high-value to low-value species, called fishing-down (or fishing-through) food webs. In many coastal ecosystems today, the size spectrum is heavily skewed towards small species, harvestable fish and invertebrates have become scarce, and their local diversity is depressed. Shelf ecosystems are often heavily trawled and formerly abundant species have been compromised, with some under strict management to rebuild their depleted stocks. Open-ocean and deep-water ecosystems are exploited by globally operating distant-water fleets, which may lack the strong oversight now seen in some coastal waters. As a consequence, there are very serious concerns about unregulated overexploitation of pelagic fish such as tuna, billfish, and sharks, as well as poorly known deep water species of diverse taxonomic origin.

In summary, the long history of fishing has drastically changed the species composition, abundance, and diversity of most coastal and shelf ecosystems, with increasing global changes seen in open water and deep-sea habitats as well. Many of these changes are poorly understood due to the ‘shifting baseline syndrome’, whereas data collection only began after many impacts had already taken place, and successive generations of people perceived the changed ocean of their youth as a ‘natural’ baseline. As populations decline, it is also difficult to distinguish the effects of fishing from those of other growing impacts such as pollution, coastal habitat transformation, and climate change. Looking forward, there is a concern that increasing industrialization of the ocean through energy projects, aquaculture, and urban expansion could accelerate the ‘defaunation’ process that began on land and is now well underway in many ocean ecosystems.

A detailed assessment of ecological change in the oceans, and its consequences for human well-being, has detailed many of the unintended consequences, including compromised productivity, ecosystem stability, fishery yield, coastal protection, and water quality. Harmful events such as toxic algal blooms, beach closures, and fishery collapses became more common

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8 D. Pauly, “Anecdotes and the Shifting Baseline Syndrome of Fisheries,” *Trends in Ecology & Evolution* 10, no. 10 (1995): 430, doi.org/10.1016/S0169-5347(00)89171-5.

9 D.J. McCauley et al., “Marine Defaunation: Animal Loss in the Global Ocean,” *Science* 347, no. 6219 (2015): 1255641, doi.org/10.1126/science.1255641.

10 B. Worm et al., “Impacts of Biodiversity Loss on Ocean Ecosystem Services,” *Science* 314, no. 5800 (2006): 787–790, doi.org/10.1126/science.1132294.
with the increasing depletion of species and degradation of ecosystems. Conversely, many of these changes were shown to be reversible when local areas were protected from fishing and direct impacts of human use. A subsequent study also showed that improved fisheries management can reverse many of the consequences of historic overfishing seen at larger scales.\textsuperscript{11} These studies provide both a warning and a hopeful incentive to reverse some of the ecological changes brought about by a long history of overexploitation.

A key challenge in contemporary ocean management, however, is to find the right balance between using ocean ecosystems for human benefit, and protecting them from deleterious change (or reversing such change where it has occurred). This challenge is amplified by global climate change, which can profoundly affect ocean ecosystems. Well-enforced protected areas in a wide range of representative ecosystems can serve as a tool to hedge against management uncertainty, but also as a laboratory to isolate the effects of certain impacts, such as fishing, from other factors, such as climate change. Marine protected area coverage has been increasing steadily at a relative growth rate of approximately 8 percent per year since 1960, and now exceeds 4 percent of global ocean area.\textsuperscript{12} Many of these areas are not well managed, staffed or funded, however, compromising their usefulness.\textsuperscript{13} Moreover, the management of fisheries in the remaining 95 percent of global ocean area has only slowly been progressing towards sustainability, and business-as-usual scenarios still project continued depletion.\textsuperscript{14} Improved management would bring about profound economic and ecological benefits, particularly in heavily exploited waters found, for example, across East Asia and Europe.\textsuperscript{15} Unfortunately, only strong political will, global enforcement of existing rules, and elevated international coordination will make this happen.

Addressing the wider ecological impact of fishing requires careful scientific analysis and the construction of ‘dose–response’ functions that examine the trade-offs between various degrees of ocean use and their ecological impacts. A recent example concerns the fishing of small planktivorous ‘forage’ fish, which represent a critical food source for many seabirds, marine mammals,
and predatory fishes. Increasing demand for fishmeal from globally expanding aquaculture and livestock operations has put growing pressure on these fisheries. A comprehensive modeling study quantified the benefits (forage fish yield) versus unintended impacts (mammals, birds, and fish species negatively affected) of these fisheries in a range of representative ecosystems (Figure 1), providing fisheries managers with a science-based decision-making tool. The study concluded that most negative impacts can be avoided by reducing exploitation rate by about 50 percent below the rate that would produce maximum sustainable yield (MSY). This management scenario still offers near-optimal yield (~80 percent of MSY) while greatly reducing associated ecosystem impacts.

Another recent paper came to similar conclusions with respect to the ecosystem effects of fishing invertebrates, and a third report showed this more generally for the effects of fishing on the collapse of bycatch and weakly productive target species. All three studies clearly indicate that traditional management targets of MSY produce large unintended consequences that can be mitigated by treating MSY as a limit, not a target. Substantially lower exploitation rates will initiate the rebuilding of fish biomass and size structure, help to recover collapsed stocks, and reverse some of the most deleterious ecosystem consequences. In the medium to long term, this will produce comparable fishery benefits, while minimizing ecosystem impacts, and reducing the cost of fishing, thus increasing the profit margin for fishers towards maximum economic yield (MEY). Therefore, reducing the exploitation rate below the level of MSY will greatly benefit fishers (greater profit and security), managers (sustainable long-term yield from a more stable and productive ecosystem), and species (fewer collapses and more robust populations). So far, very few regions may have reached this goal; however, one well-documented example concerns the California Current large marine ecosystem, where previous overexploitation has been reduced to a level that is consistent with greatest conservation benefits.

In conclusion, while ecological change is the norm over the ocean’s history, many of the changes seen in recent decades are brought about by the overuse of marine living resources, the unintended consequences of fishing, as well as other human impacts. Many of these impacts still appear to be reversible, and
few global extinctions have occurred in the ocean. Both the knowledge base and the management innovations needed to constrain or reverse deleterious ecological change do exist, and are being used in a variety of regions around the world. It is my hope that fisheries management can transform itself and may increasingly contribute towards a sustainable, resilient, and carefully managed ocean ecosystem.

**Figure 1** Modeling of trade-offs in fisheries management. The projected long-term fishery yield (thin line) is shown as a proportion of maximum sustainable yield (MSY) of targeted forage fish species. The ecological impact of taking that yield (thick line) is measured as the proportion of marine mammals, seabird, and fish species groups whose biomass varied by more than 40 percent as a result of forage fish depletion (after data in Smith et al., supra note 16). Environmental impacts of two different management strategies for maximum yield, and near-maximum yield are illustrated, respectively.