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Good fisheries management is good carbon management

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Climate change is causing persistent, widespread, and significant impacts on marine ecosystems which are predicted to interact and intensify. Overfishing and associated habitat degradation have put many fish populations and marine ecosystems at risk and is making the ocean more vulnerable to climate change and less capable of buffering against its effects. In this Perspective, we review how overfishing is disrupting the important role of marine vertebrates in the ocean carbon cycle, causing disturbance and damage to the carbon-rich seabed, and contributing to rising greenhouse gas emissions through fuel use. We discuss how implementing good fisheries management can reduce or remove many of the impacts associated with overfishing, including fish stock collapse, destruction of seabed habitats, provision of harmful subsidies and accompanying socio-economic impacts. Managing overfishing is one of the most effective strategies in protecting ocean carbon stores and can make an important contribution to climate mitigation and adaptation.

The ocean is a major carbon store that also plays an important role in buffering the impacts of anthropogenic climate change[1,2]. Over 1 million tonnes of anthropogenic carbon dioxide (CO_2) are dissolved in the ocean every hour[3], absorbing 26% of CO_2 emissions between 2012 and 2022[4], and 28% of all human-emitted CO_2 since 1750[5]. The ocean's biological pump is an important driver of the ocean carbon cycle. It incorporates a range of biological mechanisms by which the inorganic dissolved CO_2 is fixed via photosynthesis into particulate organic matter and other carbon forms through grazing processes and ultimately transported from the surface to the deep[6]. Depending on the depth of export, the carbon can be stored on the order of decades to millennia. Today, climate change and its associated impacts, alongside extractive human activities such as fishing, are interfering with the natural functioning of this biological pump and affecting the ocean's ability to sequester carbon and mitigate the impacts of climate change[1,7].

There is increasing recognition of the role of fish as "carbon engineers" that transfer, store, and release carbon[7,8]. Marine vertebrates, including fish, marine mammals, and seabirds, are becoming recognised as important players of the biological pump[8,9] as the egestion and excretion of products rich in carbon that sink to the deep sea as well as respiration of CO_2 at depth, are crucial to ocean carbon cycling[9].

Alongside climate change, overfishing is one of the greatest threats to the ocean. Decades of harvesting of marine species at unsustainable levels have led to many fish stocks being overfished[10], and the fraction of fish stocks that are overexploited continues to increase. In 2019, 35.4% of stocks were fished at unsustainable levels, compared to 10% in 1974[11], and an estimated 11% of the global fisheries catch was discarded[12]. In addition, destructive fishing gears can cause significant damage to benthic habitats and sediments[13]. The passage of bottom contact gears can disturb the upper layers of the seabed, leading to the re-suspension of sediments, re-mineralisation of nutrients and contaminants, and the removal, damage, or displacement of benthic flora and fauna[14].

Moving towards good management that ends overfishing and restores ecosystems would ensure resilient fish populations that are more capable of supporting the delivery of their ecological functions. This in turn will help sustain the contribution of fish to the biological carbon pump and draw-down of atmospheric CO_2, and the associated climate change mitigation benefits[15].

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Fish, fisheries and the ocean carbon cycle

Fish

Marine fish are essential to ocean carbon cycling and storage through a range of biological and physical processes including feeding, respiration of dissolved CO_2, excretion of dissolved organic carbon and particulate inorganic carbon (carbonates), and egestion of faecal material[6,9]. The consumption and transfer of carbon by marine fish through food webs is also a vital component of ocean biogeochemical cycling. Fish have been estimated to contribute, on average, 16% of organic carbon export from the euphotic zone globally through both passive (sinking particulate material) and active (release of particulate and dissolved respired/excreted carbon at depth from diel vertical migration (DVM) organisms) mechanisms[9]. Carbon in the tissues and skeletons of marine fish remains stored for the lifetime of an individual and is passed through the marine food web as animals are predated[8]. Faecal pellets are a naturally efficient form of carbon repackaging and, through their passive sinking through the water column, are one of the ocean's most effective natural carbon sequestration mechanisms[16]. Fish faecal pellets could be responsible for more than 20% of the deep ocean respiration and carbon sequestration fuelled by the biological pump[17], as their relatively large sizes and density facilitate rapid sinking rates[9,18].

Fish-mediated active transport of carbon through DVM of mesopelagic fish has been estimated to contribute 10%-40% of deep ocean carbon export[19] through defecation, respiration, excretion and predation at depth[9]. The mesopelagic contains the greatest abundance of fish, with an estimated biomass of up to 20 billion metric tons[20]; however, estimations of their overall biomass vary by orders of magnitude and result in significant uncertainty[20]. They are a crucial component of marine food webs, consuming a wide variety of zooplankton[21], and are a key prey item for higher trophic levels[22]. Mesopelagic fish are also a largely untapped resource for the fishing industry[23], although interest in their exploitation is increasing[24].

Fisheries

Commercial fisheries may be having a critical influence on the ocean's ability to sequester atmospheric CO_2[25]. Fishing is estimated to have halved the biomass of exploited species[26], leading to a reduction in fast-sinking faecal pellets and deadfalls and modifying vertical migrations, ultimately altering carbon export and other biogeochemical cycling[17]. Following natural death, the carcasses of fish sink to the seabed, where the carbon contained within their bodies can be sequestered into long-term storage in the deep sea or sediments[8,18]. Fisheries disrupt this natural carbon sink by reducing carcass deadfall and subsequently the amount of carbon sequestered in the deep ocean. Since 1950, fisheries targeting large fish such as tuna, sharks and mackerels have prevented the sequestration of 21.8 million metric tons of carbon[7]. Much of this fishing effort has been concentrated in the vast high seas, where up to 54% of landings would be economically unprofitable without subsidies[27]. In exclusive economic zones (EEZs) a large portion of discards and bycatch is consumed by scavengers, particularly seabirds[28], which are an important vector for nutrients from the open ocean to coastal and terrestrial ecosystems[29]. However, the consequences of this disruption in terms of carbon sequestration, particularly in the high seas, are yet to be explored.

Overfishing interacts with other anthropogenic stressors, such as climate change and pollution, exacerbating impacts and leading to lower resilience of fisheries and marine ecosystems[30]. Even fishing below the maximum biological capacity of a species without good fisheries management can adversely affect ecosystem structures and functions, for example, through the selective removal of high trophic level and valuable fish leading to less complex and truncated food webs[31]. Overfishing can induce ecosystem-wide effects as the indirect impact of removing higher trophic level species cascades through marine food webs, triggering regime shifts that impact lower trophic communities[32] and altering ocean carbon dynamics[33].

Climate change is driving shifts in the productivity and distribution of key marine fished species[34,35] and declines in fish biomass are projected to increase as extreme events such as marine heatwaves become more frequent[36]. By 2030, 23% of fish stocks shared between neighbouring EEZs will have shifted due to climate change, highlighting the need for adaptive, equitable and flexible fisheries management and stronger ocean governance to support resilient fisheries[37].

Climate change is predicted to alter mesopelagic biomass, with losses of up to 22% forecast at low and mid latitudes by the end of the 21st century[38]. The combination of increased exploitation of mesopelagic fish stocks from fisheries and reductions in their abundance as a result of ongoing climate change could lead to declines in their contributions to carbon export, and changes in biogeochemical cycling[17,25].

Seabed

Marine sediments represent a large and globally important carbon store[39], and due to the size of the ocean, marine sediments store more than double the amount of carbon in the top metre compared to terrestrial soils[40]. Organic carbon that reaches the seafloor is sequestered in marine sediments and can remain locked away for centuries[41] to millennia[39]; if left undisturbed. However, the physical disturbance caused to the seabed by bottom trawling erodes and degrades the seabed[42] by mixing and re-suspending sediments[43], leading to changes in biogeochemical cycling[44], the physical properties of sediments[45], and seabed topography[46].

Bottom trawl fisheries land approximately 19 million tons of fish and invertebrates every year—nearly one quarter of the total landings from wild-caught marine fisheries[47]. Bottom trawling causes widespread and harmful impacts on marine ecosystems, the magnitude of which is dependent on numerous factors, including substrate type, gear type and levels of natural disturbance[45]. Commercial dredges and trawls targeting demersal and benthic species, including shrimps/prawns, flatfishes and shellfish, are the most widespread destructive human activity occurring on the seabed[48]. Not only is bottom trawling incredibly damaging to the seabed and benthic fauna, it also contributes significantly to overfishing through discards. Every year an estimated 10.8% of the global fisheries catch is discarded, of which 60% is from combined trawl fisheries[12].

Erosion of fine-grained sediments rich in organic matter by bottom trawling has been found to result in a 30% decline in organic carbon compared to untrawled areas and an up to 70% depletion of labile compounds[49]. The resuspension and deposition of large volumes of sediment by bottom trawl gears results in transient biogeochemical cycling, altering the respiration pathways of organic carbon mineralisation through increased oxygen exposure[45], with the potential to substantially alter organic carbon cycling within seafloor sediments[50]. Sediment displacement caused by trawling decreases benthic metabolism through lowering oxygen consumption and simultaneously increasing oxygen demand from the water column, thus limiting the amount of carbon buried in trawled sediments[51].

The impacts on biogeochemical cycling caused by bottom trawling could be irreversible and significant, impeding carbon burial rates and capacity[49]. As sediments are trawled, the carbon stored within them can be remineralized back into the water column. A recent study estimates that bottom trawling could result in the release of nearly 1.5 billion metric tons of aqueous CO_2 in the first year[52], although these rates are debated[53,54]. Subsequent research has found 55–60% of the aqueous CO_2 produced from bottom trawling will be released into the atmosphere within nine years[55]. The effect of the residual fraction on the source-sink status of the nearby water column is unknown[55] and research needs to be conducted to provide more constrained estimates which will help mitigate the risk of mainstream misrepresentation or misinterpretation.

Emissions

Despite direct emissions from the marine fisheries sector being relatively low compared to most land-based animal protein, the use of fossil fuels as the main source of energy makes fisheries a significant contributor to global greenhouse (GHG) emissions[56]. Moreover, with 25% of the annual wild fish catch going to the production of fish meal and oil between 1950 and 2010[57], much of which is used as feed in aquaculture and for livestock, the carbon footprint of fish can become significantly higher when considering the full lifecycle of the product. The global fishing sector accounts for an estimated 1.2% of global oil consumption[58] and experienced a 28% increase in emissions between 1990 and 2011[56]. As the world's fishing fleet has evolved to be larger and more powerful, vessels are able to travel further offshore[59], increasing their fuel consumption. In addition to vessel fuel combustion, the processing, refrigeration and transport of seafood also contribute to the GHG emissions of the fishing sector[60].

Harmful fisheries subsidies, as defined in Sumaila et al.[61] are linked with increased CO_2 emissions from the fishing sector[62] as they enable fleets to fish in distant waters and the high seas[63]. Of the US$35.4 billion global fishing subsidies provided in 2018, fuel subsidies constitute 22%[64], enabling vessels to travel greater distances to remote fishing grounds in the high seas, burning greater quantities of fossil fuels[7,62]. Furthermore, these subsidies favour industrial fishing fleets, with an estimated 19% of reported global fisheries subsidies going to small-scale fisheries, even though they employ 90% of fishers[65]. Subsidies are also crucial to bottom trawl fishery economies[66] and without government subsidies deep-sea bottom trawling would not be globally profitable[27].

Overfishing contributes to increased GHG emissions as targeting overfished stocks increases the fuel use per unit of seafood landed, compared to fishing recovering or stable stocks[67]. By targeting overfished stocks, fishers may burn more fuel either as a result of travelling further offshore to fishing grounds or by fishing for longer to catch the same quantity of fish[67].

Good fisheries management

If good fisheries management is applied, the following issues are absent, summarised in Fig. 1: (i) overcapacity and overfishing; (ii) destruction of the seabed using fishing gear; (iii) bycatch and discards; (iv) illegal, unreported and unregulated fishing; (v) fishing down the food chain and truncation of marine ecosystem structure; (vi) non-cooperative management of shared fish stocks; (vii) provision of harmful fisheries subsidies; and (viii) undervaluation of ecosystem services that are not traded in the market.

Good fisheries management is linked to multiple benefits, summarised in Fig. 1. These include better ecosystem health[34]. The approach may be different depending on the fishery, but it is widely accepted that good fisheries management implements an ecosystem approach, i.e. that decision-making goes beyond seeking a maximum sustainable yield based on assessment of a single stock harvest yield and biomass[68]. Good fisheries management may include using reference points; reviewing stock assessments; accounting for illegal, unreported and unregulated catches; stakeholder engagement; and including economic and social factors in long-term management plans[34]. In the interest of food security and nutrition, future fisheries management may incorporate nutrient-based approaches[69]. Good fisheries management, by eliminating harmful subsidies, phasing out bottom trawling and regulating fishing on the high seas, would also significantly reduce fuel use in the fishing sector, leading to a reduction in GHG emissions. Good fisheries management has large co-benefits for climate adaptation for marine biodiversity, fisheries and their dependent human communities[1,70]. Intensifying climate change has been adversely impacting marine ecosystems and fisheries, leading to species range shift, changes in the timing of migration and other biological events, and shifts in ecosystem structure and functions[71]. These changes are impacting fisheries through decreases in the catch potential, economic and social benefits[72] and nutritionally and culturally important marine species[73]. This negatively affects coastal fishing communities and Indigenous Peoples, who are particularly vulnerable to these impacts, and to climate change in general[73]. Many of the impacted species are already over-exploited or depleted and in need of rebuilding their abundance and restoring their potential long-term benefits to the dependent human communities[74].

Overfished stocks do have the potential to recover, as evidenced by Atlantic cod which have not lost the genetic diversity needed for recovery despite the massive collapse of stocks in the mid-20th century due to decades of overfishing[75]. Results from numerical modelling of marine species rebuilding under climate change suggest that effective and conservation-focused fisheries management (i.e., fishing levels below maximum sustainable yield) is necessary to enable rebuilding of over-exploited biomass, particularly for vulnerable systems such as the tropics[76]. No-take marine protected areas that cover substantial distributions of the exploited species (>10%) would have additional benefits to rebuilding over-exploited fish biomass and restoring catch potential under climate change[52]. Moreover, due to the climate-induced shifting of species distribution, range overlap between targeted species and bycatch is also changing[77]. Such changes in

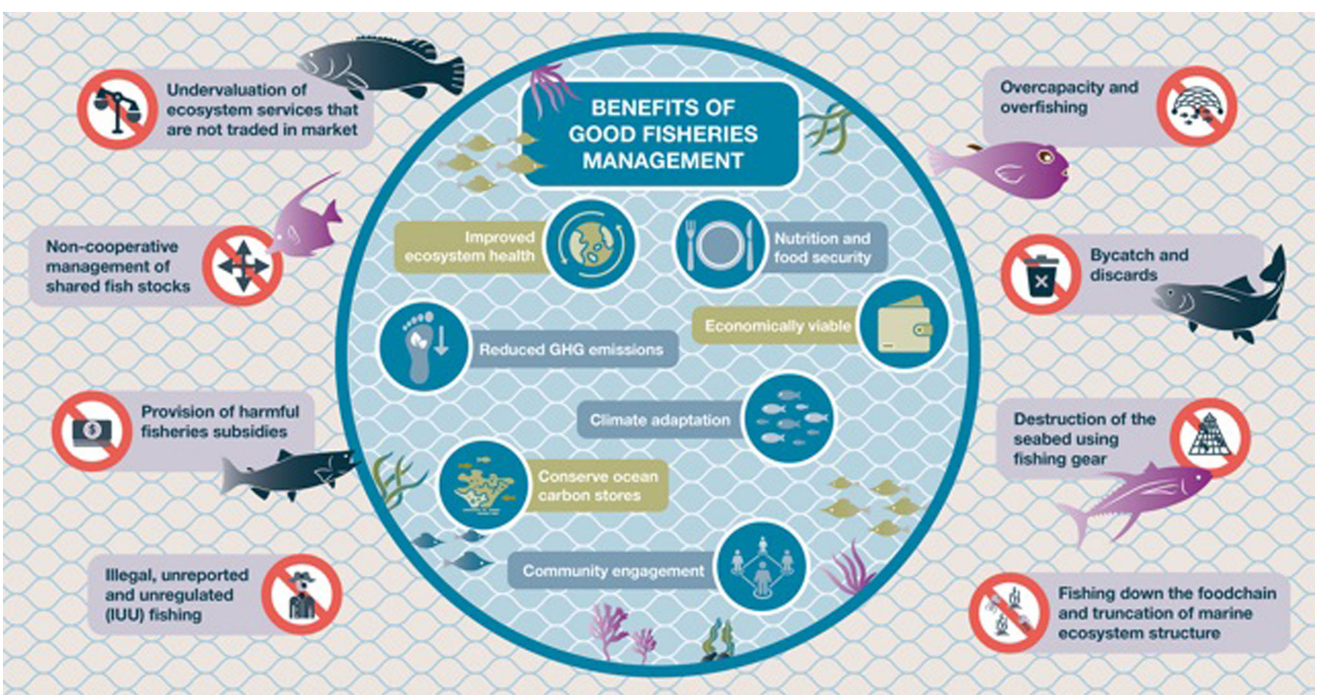

Fig. 1 | Benefits of good fisheries management and issues associated with poor fisheries management practices. Graphic summarising the benefits of good fisheries management within the blue circle, and issues associated with poor fisheries management practices identified by red circles.

range overlap are altering the impacts of fishing on species considered as bycatch. Thus, good fisheries management that monitors the changing ecology of both targeted species and bycatch could improve conservation and support sustainable fisheries. Furthermore, collection of accurate fisheries data and timely and open sharing of such data, which are characteristics of good fisheries management, are critical for rapid adaptation responses that allow fisheries to adapt to the impacts of both slow onsets changes and extreme events such as marine heatwaves[36].

The compounding effects of climate change and overfishing will disproportionately impact fisheries-dependent communities, increasing the economic vulnerability of small-scale fishers[78] and creating economic and food security challenges[79]. In addition to the environmental benefits, good fisheries management allows for the sustainable use of fish resources and ensures the socio-economic benefits of fishing. Fish and other marine resources are a vital source of food and income for millions of people worldwide, but bad fisheries management can deplete fish stocks and threaten the livelihoods of those who depend on them. To balance the negative costs of overfishing, good fisheries management employs sustainable fishing practices that aim to maintain fish populations at healthy levels.

Protecting Earth's natural carbon sinks is a low-cost and effective strategy in our fight against climate change[80], and managing overfishing is one of the most effective ways in which ocean carbon stores can be protected. Good fisheries management makes an important contribution to climate mitigation. However, the effectiveness of ecosystem-based solutions such as good fisheries management are dependent on the effective reduction of greenhouse gas emissions because of the adverse impacts of unmitigated climate change impacts on fish stocks, blue carbon marine ecosystems, and rebuilding of fish biomass[71,76].

Concluding remarks

Better fisheries management contributes positively to climate mitigation and adaptation. As fish have an important role in the carbon cycle, and fishing practices may be reducing ocean carbon stores through fishing and by trawling carbon-rich seabeds, there is a strong climate change case for ending both overfishing and phasing out bottom trawling across the global ocean. Good fisheries management that prevents overfishing and the destruction of the seabed would not only help restore marine biodiversity and strengthen food security and livelihoods but would deliver multiple co-benefits through the ocean-climate nexus. These include enhancing the carbon sequestration potential of marine organisms, building the climate resilience of marine ecosystems and the communities that depend on them, and not allowing fisheries to deplete the carbon sequestration value of marine life[81]. If fish stocks are allowed to recover, less fuel will be needed to catch the same quantity of fish, while the cessation of bottom trawling would simultaneously reduce GHG emissions, bycatch and ecosystem degradation.

There are currently several key areas where knowledge gaps are present which should be addressed in order to inform and more accurately assess how good fisheries management can mitigate climate change. Whilst not an exhaustive list, we make recommendations here for some priority areas of research. Firstly, more empirical research is needed regarding faecal carbon transport and sequestration rates of a range of fish species which is estimated to be a greater contributor to the ocean carbon sink than biomass[18]. Currently, data exist for very few wild species[8]. Secondly, modelling of carbon sequestration rates and longevity in marine ecosystems needs to be undertaken to include fish, and impacts of fishing, at a scale which is suitable for management. Thirdly, more comprehensive spatial and temporal data are required for industrial fishing fleet operations, and illegal, unreported, and unregulated fishing, both in coastal waters and the high seas. Finally, there is still much uncertainty around how much carbon is emitted due to bottom trawling disturbance to the seabed[53]. To provide more constrained estimates of carbon remineralisation by bottom trawling, future research needs to account for multiple factors including the impact of different gear types; geographic heterogeneity; the role of seabed invertebrates; improved organic carbon mineralisation rates; and, how disturbance and resuspension of sediments caused by bottom trawling compares to natural resuspension rates[53]. The phasing out of bottom trawling would also require comprehensive socio-economic and environmental studies to assess the potential impacts of a transition to alternative fishing methods, alongside rigorous analyses to refine estimates of whether alternative methods, which may fish less effectively, could inadvertently lead to heightened emissions owing to prolonged fishing duration.

Overfishing and marine habitat degradation threaten ocean biodiversity and reduce the ability of the ocean to buffer the impacts of climate change. By taking an ecosystem approach that integrates climate and carbon sequestration considerations into decision-making, good fisheries management can be an important contributor to global efforts to mitigate the impacts of climate change.

Data availability

Data sharing is not applicable to this article as no datasets were generated or analysed during the current study.

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