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ABSTRACT

Replacing animal protein sourced from marine capture fisheries with animal protein from agriculture will likely increase the threats to biodiversity given current human diets. Approximately half the Earth's arable land surface has been converted from natural habitats to food production which has been identified as a key driver of biodiversity loss in terrestrial ecosystems, as have fisheries in aquatic environments. Reductions in seafood production arising from major reductions in access to fishery resources and consumption would affect the demand for agricultural land. Replacing all animal protein from marine fisheries could require almost an additional 5 million km^2 of land – larger than the extent of intact rain forest in Brazil – if replaced by the current proportional combination of livestock and poultry. Replacing all fish in aquaculture diets would result in the need for over 47,000 square kilometers of new land converted to agricultural production. Concomitantly, data show that terrestrial and freshwater species are more likely to be threatened with extinction than marine species and that agriculture is the dominant cause of these extinctions. This paper suggests that extinction risks per million tonnes of animal protein produced are 2.6 times higher for agriculture than marine capture fisheries. Agriculture is the main driver of extinctions because it is predicated on the conversion of complex, natural ecosystem structures to simple, human-dominated systems, whereas well-managed fisheries seek to work within natural ecosystem structure and function. Available evidence suggests that relying even more on land-based animal foods by replacing marine with terrestrial protein sources may cause more biodiversity loss, not less. Policy makers need to consider the implications of restricting the use of fishery resources on planetary biodiversity beyond measures aimed at attaining sustainable use.

KEYWORDS

Agriculture; land conversion; biodiversity; fisheries; plant-based

Introduction

Consumers, especially in the global North, live in a sea of claims about the sustainability of various foods (Silver and Hawkins 2017). The documentary Seaspiracy claimed that sustainable fishing is not possible (Sivertsvik 2021) and the more recent documentary Oceans will have raised questions about seafood consumption in the minds of millions of people. Reynolds et al. (2014) note that changing diets to meet sustainability concerns is a relatively recent phenomenon but that environmental considerations are now creeping in to official dietary advice in some countries. Furthermore, Reynolds et al. (2014) note that reducing the consumption of meat and fish will have environmental benefits (from an energy perspective) but that it is unlikely that this will occur.

The underlying assumption is that the comparative impacts of agriculture versus fisheries favor agriculture, but this may not be the case, especially when biodiversity is the basis for the comparison. This paper evaluates some potential consequences of major changes to fishery resources access resulting from concerns about the impacts of fishing. The central theme is an examination of whether the replacement of marine-sourced animal proteins environment by

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land-sourced proteins would be beneficial for global biodiversity. Calculations of land use change and data on documented threats to biodiversity by agriculture and fishing are used to investigate how impacts on biodiversity are or may be affected by different dietary choices.

Agriculture and fish production affect biodiversity

The expanding global population and growing per capita wealth is driving an increasing demand for food (Shukla et al. 2019) and an increase in the trophic level of human diets (Bonhommeau et al. 2013), which has been contributing to further conversion of land use to agriculture (Gibbs et al. 2010). There is considerable concern that the growth in food production will further aggravate biodiversity declines (Chaudhary and Kastner 2016; Tilman et al. 2017). Despite a major extinction crisis unfolding as a result of human activities, the comparative impacts of different food production systems on biodiversity are scarcely considered, especially in policy decisions (but see (Walker et al. 2021; Unep 1992)

Food production is the dominant human use of both the land and ocean. About half of the total habitable terrestrial surface is used for agriculture (Shukla et al. 2019; Winkler et al. 2021), of which 77% supports animal production (mostly cattle) and the remainder is used for crop production of which about a third is used for animal feeds (Poore and Nemecek 2018). For farmed aquatic animals about 73% were fed (i.e., not filter feeders) and this percentage has continued to grow (FAO 2024) and the majority of farmed/fed aquatic animals rely on some percentage of fishmeal in their diets (Tacon and Shumway 2024). For some farmed species (e.g. Atlantic salmon *Salmo salar*) the amount of fishmeal in the diet has been reduced significantly over the past 30 years (Aas et al. 2019) with soy being the main protein replacement in commercial feed. About 38% of animal aquaculture is marine based, but finfish production from freshwater is over 6 times that from marine waters (FAO, 2022). Most continental shelves are intensively fished, and there is some fishing for tunas and large pelagic fishes on roughly half of the high seas (Kroodsma et al. 2018).

There are choices to be made as to how more food will be produced and what land use and biodiversity consequences will be produced from these decisions (Freeman and Zimmerman 2023). While there are an increasing number of studies comparing food production systems from a variety of environmental perspectives (e.g. greenhouse gas production, water use, pollutants, amongst many others) (e.g. (Xia et al. 2023)), the comparison of biodiversity impacts, especially across significantly different systems such as wild harvest and farming, is rare due to the complexity of such calculations. Biodiversity loss is a source of significant global concern (Díaz et al. 2019), and understanding the interactions between provisioning pathways, human diet, and biodiversity will be critical for the sustainable management of food systems and resolving the tradeoffs required (Dalin and Outhwaite 2019). This paper focuses on human diets because the planetary consequences of how much and what types of food humans consume are increasingly of interest as pressures on the climate, people, and biodiversity attract scrutiny.

Food production has impacted native biodiversity for millennia (Stephens et al. 2019). Early human societies have been implicated in the decline of megafauna (Svenning et al. 2024), extirpation of coastal resources (Poiner and Catterall 1988) and habitat alteration (Muhly et al. 2013) including *via* the use of fire (Thompson et al. 2021). In the last few centuries, this impact has expanded dramatically with deforestation across Europe (Kaplan et al. 2009), conversion to agriculture of the Great Plains of the US and the Eurasian steppes (National Research Council 2005; Kamp et al. 2015), the more recent development of global large scale fisheries (Swartz et al. 2010) and aquatic farming practices, such as shrimp ponds replacing mangrove forests (Ashton 2008). The post-World War II period has been termed 'The Great Acceleration' (Sasges 2020) due to the growing scale and diversity of human impacts on the planet. Many of these changes are continuing and unevenly distributed, with most new agricultural land in recent decades being developed in tropical forests (Gibbs et al. 2010; Shukla et al. 2019). Approximately 83% of the expansion of global agriculture in the 1980s and 1990s replaced tropical forests, leading to biodiversity loss in some of the most species-rich habitats on earth (Gibbs et al. 2010). The scale of the issues generated are huge, with (Singer and Kristiansen 2023) labeling "petroleum-intensive industrial agriculture as one of, if not the, most ecologically destructive human enterprises in recorded history."

On land, there are many mechanisms that drive biodiversity loss including land conversion, urbanization, water extraction and dam construction, introductions of non-native species and diseases, consumptive use of wild animals, plants and fungi, and agricultural inputs (fertilizers, pesticides, medicines) and persistent contaminants (e.g., the use of plastic mulches) (IPBES 2019). Human use of the land commonly creates homogenous landscapes where there

was once diversity. The most transformative activity on land is forest clearing for the raising of crops or for cattle production (Zu Ermgassen et al. 2020), since it usually involves elimination of native vegetation and replacement with non-native or even genetically modified species and is commonly irreversible for centuries (Isbell et al. 2019). A substantial amount of literature compares biodiversity measures across a range of habitats and land use (Newbold et al. 2015). This understates the loss of native biodiversity in agriculture because crops, weeds, and agricultural pests are often included in species counts, and many species that become more abundant after conversion of land to agriculture are not species of conservation concern. It is precisely the species that do not tolerate agriculture that are increasingly at risk of extinction (Phalan et al. 2011; Tilman et al. 2017). Land-based food production also contributes to impacts on marine and coastal systems when agricultural wastes (slurry) and chemicals enter river catchments that discharge to coasts (Tomašových and Kidwell 2017). The only documented example of marine harvest impacting terrestrial ecosystems is the reduction of anadromous salmon populations (Schindler and Smits 2017).

In aquatic food systems (capture and culture), the major impacts are direct removals of both target and non-target species, the ecosystem impacts of those removals, provisioning *via* discards, loss of non-biodegradable gear, predator culls or entanglements, non-native introductions, chemical treatments and water pollution, and habitat modification. Fishing gear has also been shown to negatively affect biodiversity, such as trawls depleting benthic species richness (Hiddink et al. 2017) and nets, traps and lines causing accidental animal mortality (Anderson et al. 2011; Žydelis et al. 2013). Fishing, unlike agriculture, primarily impacts higher trophic levels, leaving the base of the food chain far less affected. In the marine environment, published estimates suggest that only the abundance of high trophic level fishes has been significantly reduced by fishing, while lower trophic level fishes are on average twice as abundant as they were before industrial fishing (Christensen et al. 2014), although there may be localized impacts (Anderson et al. 2011), especially on some dependent predators such as seabirds (Duffy 1983; Furness 2003; Smith et al. 2011; Sherley et al. 2017; Smith et al. 2019).

Reducing fishing, increasing land demand

The need to restrict fishing to meet sustainability needs is not disputed. Over multiple jurisdictions, clear benefits for fish stocks, bycatch and marine ecosystems have arisen from decisions aimed at cutting fishing capacity and effort, controlling catches and, where needed, rebuilding stocks (Fulton et al. 2019; Hilborn et al. 2020). Calls to restrict fishing for reasons other than meeting sustainable use requirements are common and often have roots in calls for a greater share of the catch from one user group over another (Charles 1992; Fritchey 1993; Seng et al. 2005; Loring 2017). Calls increasingly focus on widespread bans that go beyond local disputes between user groups or between nations. Such calls include *in extremis* elimination of marine fishing (particularly commercial fishing and 'industrial' or fed aquaculture) either specifically or as part of campaigns to stop the use of animals more widely (Fennell 2013; Deckers 2016; Freeman and Zimmerman 2023). Other proposals include banning whole classes of fishing gear, such as trawls (Watling and Norse 1998; Watling 2013) or nets generally or in specific regions. There is a global campaign to ban fishing in large areas such as the high seas (White and Costello 2014) or 30% of the world's coasts and oceans (Agbor 2022). Finally, some have advocated to restrict or eliminate the use of fish products for certain uses such as marine ingredients in fed aquaculture (Pikitch et al. 2014), arguing that the use of plants in aquafeed has a lower environmental impact or proposing that fish should only be used only for direct human consumption (Tacon and Metian 2009; Cashion et al. 2017).

In light of these increasing pressures to restrict fishing for reasons beyond meeting sustainable use requirements, there is a pressing need to evaluate the likely consequences of such decisions which may have unintended consequences for terrestrial biodiversity and other system components. There are other protein sources available to replace fishmeal use in aquafeeds (see for example (Hodar et al. 2020; Fisher et al. 2020), but the dominant option has been crops–primarily soy due to its price and availability–and soy will be the main protein replacement crop considered in the present study.

While land use is not a direct measure of biodiversity loss, it is the major driver of biodiversity loss globally and can thus help generalize a broader level of potential impacts to biodiversity if marine resources were replaced by land-based production.

Calculation of land needed to replace animal protein from wild harvest fisheries

Based on the total tonnes of protein from wild capture fish (tonnes of wild capture fish times the useable weight conversion times the average protein content of fish) the number of 100-g servings of protein from wild fish is the total tonnes of protein times 10^4. The number of km^2 needed to replace fish production by

different agriculture-based diets is the number of 100-g servings of protein from capture fisheries times the area needed per 100 g of protein from the alternative sources (Supplemental Table S1), times 10^6. The current global mixture of protein production from livestock is beef and lamb (25%), chicken (40%) and pork (35%), which is taken from the OECD's meat consumption indicator (OECD 2022).

For the case of fed aquaculture, the amount of protein in fishmeal used in aquafeeds is the tonnes of fishmeal used in these feeds from reduction of whole fish times the average protein content of whole fish plus the tonnes of fishmeal from fish trimmings times the average protein content of the trimmings. The protein per square km from soy is the yield of soy per ha times 100 times the average percentage of protein in soy. The area required to replace the protein used in aquaculture from fishmeal with soy is the amount of protein from fishmeal used in aquaculture divided by the protein per square km from soy.

To provide an indication of the scale of the land required, and in accordance with the published literature identifying tropical rainforests as the new frontier for agricultural land production the area of intact Brazilian rain forest required to replace fishery produced protein is used.

Each of the parameters used in these calculations are based on published sources and are listed in Supplemental Tables S1 and S2.

Assuming that current fish consumption would be replaced by the current proportional composition of livestock, an additional 4.99 million km^2 would be required, corresponding to 152% of the intact rain forest in Brazil (Table 1). Replacing the current protein from fish consumption by grains would require only 481,390 km^2 and 230,230 km^2 by soy (15% and 7% of intact Brazilian rain forest, respectively). Also shown is the amount of land required for the replacement of 1000 tonnes of marine fish. In addition, replacing marine fish protein in -animal feed with soy would require up to an additional 47, 453 km^2 of land. This latter figure is based on

1. The annual use of about 16MMT of directly targeted small pelagic species (Marine ingredients production | IFFO - The Marine Ingredients Organization),
2. About 5MMT of bycatch. This figure is an estimate based on estimates of 1.7MMT (Funge-Smith et al. 2012) and 10MMT (Funge-Smith et al. 2005). The latter derived data from a specific study of the use of so called 'trash fish' in aquaculture.
3. About 12MMT of trimmings (waste products from fish processing) used to produce fishmeal/oil (Marine ingredients production | IFFO - The Marine Ingredients Organization),

Extinction risk and causes

The International Union for Conservation of Nature (IUCN) Red List is an authoritative source of both species status information and key threatening processes. For species listed as Critically Endangered (CE), Endangered (E) and/or Vulnerable (VU) and where there are taxonomic representatives for land, marine and freshwater/estuarine realms, IUCN data sourced in May 2025 were used to explore the following:

1. Agriculture is more of a threat to biodiversity than fishing;
2. Agriculture is more of a threat to plants and animals in aquatic habitats; and
3. Agriculture is more of a threat than fishing to specific taxonomic groups including, bony fishes, chrondrichthyans, mammals, birds, molluscs, reptiles and crustaceans (Malacostraca). The bases for the conclusions presented below are set out in S3.

Transferring animal protein production (from capture fisheries) to the land from the sea would impact the full range of taxonomic groups (plants and animals), including those on land and those in aquatic systems not affected by fishing. The IUCN database separates threats from the growing of crops and animals from

Table 1. Median land area impact of elimination of marine fisheries production.

Marine fish replaced by	Additional land area needed (km^2)	Standard deviation	Proportion of intact Brazilian rainforest needed (%)	Land needed (km^2) per thousand tonnes of lost marine fish
Beef and Lamb	17,162,600	16,740,890	524	187
Chicken	743,015	179,807	23	8
Pork	1,151,150	709,548	35	13
Livestock* mix	4,990,759	2,981,214	152	62
Farmed fish	387,205	74,884	12	4
Grains	481,390	391,164	15	5
Soy	230,230	70,168	7	3

*Livestock – 25% beef and lamb, 35% pork 40% chicken.

threats arising from production from plantations and forestry. Whilst acknowledging that there is a wild harvest of seaweeds and possibly other aquatic plants (e.g. saltmarsh plants, seagrasses) the latter are in small proportions and are not considered further.

If all plants and animals are included the numbers of species at risk (Critically Endangered, Endangered and Vulnerable) due to agriculture (animal and crop production but not plantations/forestry) is about ten times that due to fishing (22,728 species versus 2143).

For animals and plants living in aquatic environments agriculture is a greater risk than wild harvest fishing (Figure 1). Agriculture has an impact on marine species which may have some connection with the land such as some seabirds, reptiles and mammals.

In freshwater/estuarine systems the threats to animals in particular can come from both agriculture and fisheries. An example would be the construction of agriculture water supply dams in fished rivers where interruptions to migration, changes in seasonal flow regimes and abstraction of water will exacerbate fishing pressure.

With the exception of sharks and rays the number of freshwater/estuarine species threatened by agriculture exceeds the number threatened by fishing, and this is particularly marked for invertebrates (crustaceans and molluscs) but is also true for mammals, birds, bony fishes and reptiles (Figure 2). Even in the marine realm, where fishing affects nearly three times as many species as agriculture (due to the general absence of agriculture), agriculture is a listed threat for numerous marine species of birds, reptiles and mammals due to impacts on coastal habitats, such as wetlands. Sharks and rays are the only group where fishing is listed as the primary source of threat in both marine and freshwater environments.

Agriculture would threaten both land and aquatic plants and animals if protein production were to be shifted from the marine environment on to the land. For the example taxa in Figure 2, about two-thirds to three-quarters of all species at risk on land are threatened by agriculture, noting that there may be other stressors operating as well.

Based on the method set out in S3, the number of species of plants and animals at risk from direct animal production (IUCN category 2.3) is 14,193. For crops only, i.e. no plantation forests (IUCN categories 2.1) the figure is 24,490. If 35% of these are allocated to the growing of crops for animal production (Poore and Nemecek 2018) the total numbers at risk from animal production is 22,728. Recent annual global production volumes of 357 MMT for livestock and 90 MMT for fisheries, suggesting that the numbers of plants and animals at risk per million metric tonnes of animal meat produced due to each production system (agriculture and wild fisheries) is about 63 for livestock and 24 for fisheries.

Based on assumptions about the unlikely possibility of a shift away from animal proteins in human diets (FAO 2016, 2019; Poore and Nemecek 2018) the replacement of marine capture fisheries production by land based animals production could put 2.6 times the number of species (plants and animals) at risk of extinction.

Comparison of trophic level impacts in terrestrial and marine environments

Although there may be a variety of reasons why there are differences in the numbers of species at risk due to agriculture versus capture fisheries–especially scale of production–it is possible e that one additional reason may be that the two production systems are

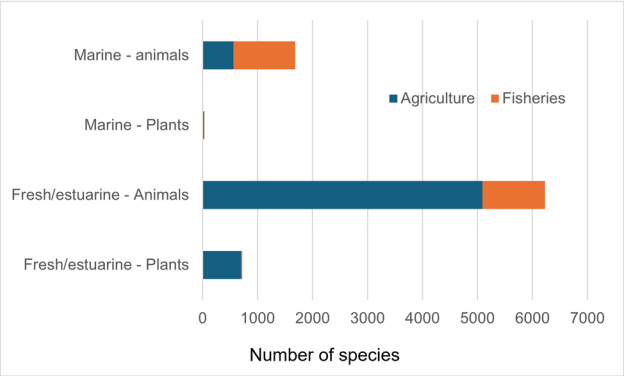


Figure 1. Numbers of aquatic animals and plants put at risk of extinction by agriculture and fisheries. Source: IUCN Redlist, accessed May 2025.

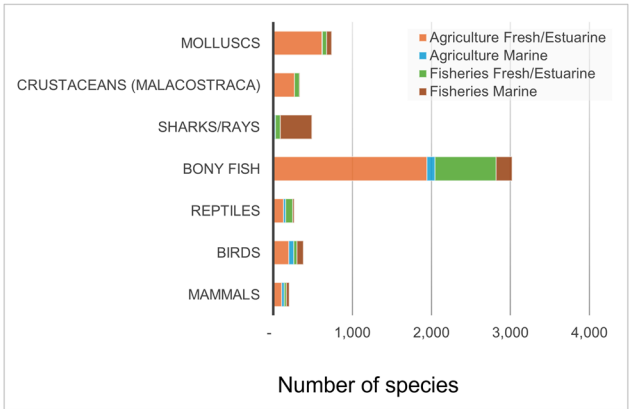


Figure 2. Numbers of aquatic species at risk (Critically Endangered, Endangered, Vulnerable) occurring on land or in freshwater/estuarine habitats that are listed as being threatened by agriculture and/or fisheries. Source: IUCN Redlist accessed May 2025.

focused on different trophic levels. Agriculture is largely focused on replacing the base of the food chain (Trophic Level 1) with desirable plants (either for direct human consumption or to support animal production) (Newbold et al. 2020), whereas capture fisheries primarily exploit trophic levels 3 and above. Cropping, in particular, is based on the removal of native species and their replacement with those desired for human food and fiber. With the exception of demersal trawling in some habitats, fisheries production is not based on habitat removal or replacement, and Trophic Levels 1 and 2 are rarely impacted by fishing. For example, in the case of krill (*Euphausia superba*), a Trophic Level 2 species, only about 1% of available production is taken each year (Nicol et al. 2012). Supplemental Table S4 summarizes the impacts on different trophic levels of crops, grazing, and fishing and an overview is provided graphically in Figure 3.

In the case of land use, there is generally a reduction in the abundance and richness of higher order carnivores (Barnes et al. 2017; Newbold et al. 2020), but the mechanisms driving such changes may be varied and may include both direct effects and indirect effects *via* trophic interactions. Some functional groups may be favored by land use changes and these changes may have cascading effects on other trophic levels. For example, (Muhly et al. 2013) found that human intervention changed an ecosystem from one controlled by top-down predation to one driven by bottom-up alteration of lower trophic levels. (Henderson et al. 2020) found that land-based impacts (urbanization and grazing) may affect adjacent waterways and may increase functional diversity due to habitat diversification, but generalists that can exploit a diversity of habitats are generally favored.

Tradeoffs needed to minimize impacts

The production of sufficient food to feed a growing global population continues to confront policy makers, producers and consumers with a plethora of issues. Policy makers in particular can be bombarded with advice that delivers simple solutions to complex situations, often with scant attention to the negative consequences and despite evidence that removing entire categories of food is fraught (Vieux et al. 2020), in addition to being extremely unlikely (Ferraro et al. 2022). This is particularly the case for the debates over the use of animals versus plants in human diets.

The compelling nature of many environmental challenges has created an urgency amongst advocacy groups to seek definitive action by governments. Calls for complete bans on certain activities are common, as exemplified by calls to ban native forest logging (Readfern 2020), bottom trawling (Buitendijk 2021), fed aquaculture (Anonymous 2021) and beef production (Anonymous 2024), amongst many other human activities. When social choices are considered, there is little likelihood of a global adoption of a vegan diet. While some public policies such as subsidies for meat and dairy production in the US and EU have influenced production (and thus diets (Winders 2009)), major modern-day food shifts appear to be rare globally (Ferraro et al. 2022). Banning of some or all of fisheries would also pose major social equity issues (Klein et al. 2015), as fisheries are central to the culture and food production opportunities of many communities around the world.

It is widely accepted that land use change is the major factor driving global biodiversity loss (Chaudhary et al. 2016) and food production has been

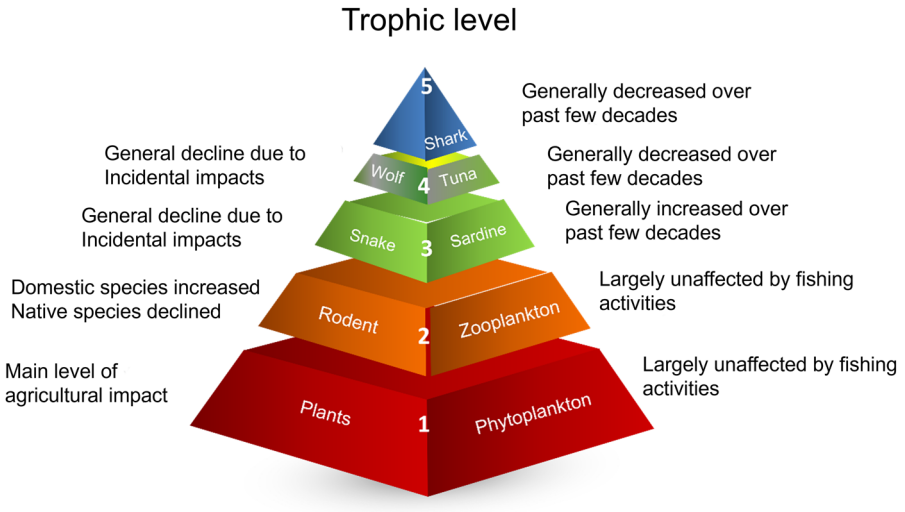


Figure 3. The degree of impact at each trophic level for agriculture (left) versus fishing (right).

the primary cause of land use change. Given the efficiency of eating plants directly (see for example (White and Hall 2017)) instead of feeding livestock, moving human diets to more plants and fewer livestock would likely have biodiversity benefits as less new land would be needed to expand food supply (Cleveland and Gee 2017; Luzzani 2022). If a major switch from livestock to plant diets was to take place, the total area needed to produce food could decline despite an expanding population. Whether this is also the case for replacing fish with plants is open to question, as a number of studies suggest that the environmental impact of fisheries production is lower than that for plants (Papatryphon et al. 2004; Boissy et al. 2011; Ghamkhar and Hicks 2020). None of these studies explicitly considered biodiversity impacts *per se*. but (Newton et al. 2023) had similar findings and noted that factors such as fish stock status need to be considered separately.

Higher risks of agriculture may be hard wired into its production strategy

One hypothesis for explaining the greater biodiversity impacts of agriculture relates to the differences in exploitation strategies pursued by wild capture fisheries versus agriculture. For the past forty years or more, the focus of fisheries management has been on selective harvest with an aim to conserve ecosystem structure and function. By contrast, agriculture is reliant on the removal of existing ecosystem structure and function and its replacement by a small number of largely introduced species. With about 60% of global fish catches being taken by gears which do not impact habitats in the way that agriculture does, this may account for at least some of the observed differences. Although about 55% of the global ocean is fished (Kroodsma et al. 2018), this is largely for tunas (Trophic Level 4) that are taken with no habitat interaction. Even if demersal trawls are included, Amoroso et al. (2018) found that the proportion of the continental shelf impacted by bottom trawling varied from a few percent Australia, Alaska and Chile to a high of 80% in the Adriatic Sea. Most areas with data available showed 10-30% of the continental shelf impacted by trawls. (Pitcher et al. 2022) found that the status of benthic ecosystems in most places where there were available data had been depleted less than 20% by trawling. To claim equivalence between the occurrence of trawling versus the increasingly widespread removal of complex and species-rich terrestrial habitats such as rainforests distorts the debate over fishing versus agriculture.

In the past, demersal trawling has been compared to land conversion (Watling and Norse 1998) in terms of its impact on habitats but notwithstanding some clearly problematic trawl activities in complex deep water most trawling takes place in shallower waters on mobile sediments where faunal recovery rates are relatively rapid (Hiddink et al. 2017). Even in circumstances where there is clear evidence of ecosystem change driven by fishing activities (such as the Gulf of Thailand (Pauly and Chuenpagdee 2003) these changes are generally viewed as being due to inadequate management as opposed to being the desired (and planned) outcome of good practice. Agriculture cannot be practiced without habitat removal and its replacement by desirable species. Global concerns (and some action) about deforestation represent welcome questioning over the complete ecosystem modification required to support agriculture but putting progress under pressure by shifting animal protein from sea to land seems questionable, especially when there is a growing number of examples of successful fisheries management.

Feeding more plants to fish may increase biodiversity losses

Completely replacing fishmeal in aquaculture with soy would demand almost 47 453 km^2 of new land. Even if only whole-fish reduction to meal was eliminated, it would require over 20,000 km^2. This is not to say alternative feeds should not be adopted, they should and are (Cottrell et al. 2020; 2021). Tonnages of fed aquaculture species will not be able to grow without doing so, given that small pelagic fish are a limited resource (Froehlich et al. 2018; Cottrell et al. 2020). Full replacement with soy–if all fed cultured species are not negatively affected (e.g., higher feed conversion ratios, see (Cottrell et al. 2020) – would have land-based tradeoffs. If biodiversity had been a key metric, the benefits of sourcing fish from a well-managed fishery (as discussed in this paper and also by Eroldoğan et al. (2023)) would have made the impacts of soy production more prominent.

Tools required to conduct objective and more localized comparisons are needed

Seeking the diet with lowest biodiversity impact requires a comparison of the biodiversity impacts of animal protein production on land to fishing in the seas. At one level, the comparison is straightforward: agriculture is almost totally transformative of ecosystems while most fishing leaves the base of the food

chain intact and primarily impacts the high trophic levels (Duarte et al. 2009). There are many uncertainties in the calculations presented above, from by-product utilization to country-specific differences in the efficiency of different food production systems and the land area needed. All calculations point to similar conclusions about changing diets and biodiversity impacts, which is consistent with the broader literature.

If volume of production is the main driver, then the push toward good fisheries management, which recognizes that there are limits to wild harvest fisheries, provides hope that marine extinctions can be limited. This contrasts strongly with the land where, despite growing concerns about deforestation, there seem to be few if any enforceable limits on land conversion, and land clearing for agriculture remains a planetary issue owed to lack of or poorly enforced controls in countries such as Brazil, Indonesia and Australia, amongst many others (Turubanova et al. 2018; Howard 2020). Whilst there are less impactful farming methods than monoculture crops, there is limited potential to produce food on land without removing native vegetation.

Diets that reduce livestock consumption or replace meat with plant-based foods would lead to reductions in land area needed and thus in expected biodiversity impacts; but how can the claimed biodiversity benefit of eliminating marine fisheries, or marine ingredients in aquaculture, be compared to the increased terrestrial production needed to compensate? In describing how much land is required to replace 1000 tonnes of marine protein, this paper provides an estimate of the potential for species loss *via* linking this marine protein to areas of land. The estimate provided above, that the risk of species loss from agriculture is 2.6 times the risk attributable to fishing, provides an estimate but this will be highly variable depending on the types and locations of fisheries and replacement agriculture replacement sources involved

Seafood is just starting to be considered as part of the wider global food system (Olson et al. 2014; Farmery et al. 2017; Tigchelaar et al. 2022), but tools for comparing biodiversity impacts across land- and water-based food production systems, such as Life Cycle Analysis (LCA), often do not adequately cover biodiversity impacts of plant production alone, and seafood production even less so (Curran et al. 2011; Notarnicola et al. 2017; Winter et al. 2017), although this is changing (see for example (Crenna et al. 2019; Chaudhary and Brooks 2018).

Ecosystem models and input-output models are valuable tools for exploring different food-impact scenarios. Exploitation patterns have a big influence on biodiversity loss, in both agriculture and fisheries. Mosaics in agricultural landscapes are less impactful than monocultures (Tscharntke et al. 2005), though this is highly dependent on yields (Phalan et al. 2016). In fisheries, so-called 'balanced harvest' may be less risky for biodiversity than selective fishing (Garcia et al. 2012), but not less risky economically (Burgess and Plank 2020). Integrating such models with the LCA approach could lead to a variety of tools that can explore food production alternatives across production systems, along the supply chain and with varying degrees of management interventions.

Comparisons have important implications for landscape and marine conservation. As stated by Fischer and Lamey (2018) comparing the impacts of different production systems is important from a variety of perspectives including ethical considerations and the costs and feasibility of implementing change. For example, (Smith et al. 2019) point out that whilst a transition to full organic production in British agriculture would have benefits in Britain, the shortfall in food production would have to be made up by making more agricultural land available elsewhere thus creating both ethical and biodiversity concerns (Balmford et al. 2025). There is considerable debate about the relative impacts of land sparing versus land sharing (Phalan et al. 2011; Newbold et al. 2015) and which would be the best strategy for increasing food production whilst protecting species. Similarly, in the marine environment, the current, dominant, approach to fisheries management (Tlusty et al. 2019) is focused on the selective harvest of a small number of species, which suits Western diets and marine ecosystems with low diversity but high abundance. In tropical systems, with high species diversity and, especially where people consume a wide variety of species, selective fishing may not be the most appropriate approach to management from either an ecological perspective (Garcia et al. 2012) or a dietary perspective. Thus, on both land and in the sea, there needs to be a rethink of the best approaches to food production if biodiversity considerations are to be incorporated into decision-making processes.

Good fisheries management is undervalued

One area which does not feature in any of the papers reviewed, especially those that attempt to deal with fisheries, is the potential benefits of effective fisheries management as an impact mitigation tool (Fulton et al. 2019). Good data and effective controls on fishery harvests can be successful in terms of managing individual species constraining ecosystem change, and

preventing loss of iconic species across gear types and jurisdictions (Fulton et al. 2019; O'Hara et al. 2021) Similarly (Hilborn et al. 2020) demonstrated that many of the world's key assessed stocks are sustainably managed and have recovered since fishing pressure was reduced. Incorporating the effectiveness of management not only provides a mechanism for separating well-managed fisheries from fisheries in general, but also a pathway forward for those that seek to mitigate impacts and thus comparisons with other food sources.

Improved management of fishery resources could result in significant increases in catches, estimated to be in the vicinity of 16 million tonnes (Costello et al. 2016) *via* traditional management techniques. Shifting to a 'balanced harvest' approach may create additional gains (Garcia et al. 2016; Kolding et al. 2016) including an increase by about a million tonnes per year for inland fisheries in Africa alone (Tous 2024). Thus, shifting protein sourcing to well-managed fisheries could save land-based biodiversity.

The coastal zone has always been heavily utilized with well known impacts on fisheries *via* pollution, habitat loss and displacement of fishing activities arising from competing uses (Caddy 1993; Rabalais 2015; Brown et al. 2018). The spatial scale of these usages is expanding with the development of energy production (oil/gas, wind), the growing needs of shipping and the need to set aside migration paths for whales (Barlow and Torres 2021) and turtles (Iverson et al. 2020). Marine spatial planning has been developed as a tool for ensuring that fish resources can be protected/restored and the supply of food can be continued (Ehler 2021; Santos et al. 2021).

Choices are set to become even more complex

The challenges are likely to become more complex in the future. Already there are fish-free 'seafood' products available that are manufactured from plant materials and sold with claims of being more sustainable. Such claims need to be viewed with some skepticism, as the exact basis for the claim may be neither clear nor independently verified. Further, the research that has been done (e.g., cell-based seafood) indicates a long and narrow path to achieve conservation benefits for the ocean, if any (Halpern et al. 2021). For example, a product made from soy grown in France claiming to imitate deepwater trawl fish will have a very different basis for a claim than one made from soy grown in Brazil claiming to be artificial tuna. The nutritional profiles of plant-based 'seafoods' are likely to be very different from the original products (van Vliet et al. 2021), and consumers need to be aware that they may not be getting the nutrition that they are expecting, especially when these artificial seafoods are highly processed (Monteiro et al. 2024). In addition, counterintuitive environmental impacts can occur if disadoption of the high-impact foods (e.g., beef) are not the outcome of dietary-shift initiatives (Cottrell et al. 2021). As food production systems introduce lab-grown meat and seafood, there needs to be transparency around the sources of the building blocks used, including how and from where they are sourced and how they were grown. Even then, the potential environmental benefits to be realized from lab-based animal proteins likely differ substantially between land versus aquatic systems (Halpern et al. 2021).

The ultimate drivers of the increasingly tough decisions about the future of the world's species and habitats are related to the increasing numbers of people and their growing wealth, and importantly overconsumption by the wealthiest nations. Policymakers require information on the consequences of decisions to substitute one source of food for another in order to avoid a leap from the frying pan into the fire.

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Data availability statement

The data and calculations that support the findings of this study are available in the supplementary material of this article.

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