Scoping report:

The role of seafood in sustainable and healthy diets

The EAT-*Lancet* Commission report through a blue lens

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1. Introduction

The EAT-*Lancet* Commission report

One of the greatest challenges facing humanity today is how to feed a growing world population a healthy diet, produced in ways that do not threaten key Earth system processes. The EAT–*Lancet* Commission report on healthy diets from sustainable food systems was launched in January 2019 and provides a major contribution by setting scientific targets for healthy diets and environmentally sustainable global food production systems.[1] These include a healthy reference diet, based on a daily intake of 2500 kcal per day, and identification of scientific targets for six key Earth system processes of direct relevance to food production: climate change, nitrogen and phosphorus cycling, freshwater use, biodiversity loss and land-system change.

The scientific targets in the EAT-*Lancet* report for sustainable food production systems were set to make sure that the food system is not pushing the planetary boundaries (PBs) past their identified thresholds. Thus, contrary to the health targets, no specific goals for individual foods, species or commodities were identified, but the set boundaries considered the food system as a whole.

In order to investigate the compatibility of healthy food and sustainable production systems, in light of a growing world population, a food systems model was created with the aim to investigate whether it is possible to transition to the "Planetary health diet" by 2050 (based on scientific health targets) whilst simultaneously staying within the food planetary boundaries (targets for environmentally sustainable food production systems). The model converted projected consumption patterns to requirements for food production. Future demand for food in different regions of the world was assumed to be influenced by population and income growth. Increased GDP in a country is expected to increase demand for animal-sourced products (including seafood), fruits and vegetables.

Key messages:

- Seafood as a dietary component has many human health benefits and many are connected to the consumption of important omega 3 fatty acids.
- All currently available estimates of future projection show limited growth for the capture sector, indicating that the lion share of future seafood demand will have to be produced through aquaculture.
- A comparison of future production estimates with the healthy reference diet, as recommended by the EAT-*Lancet* Commission report, shows a potential production-consumption gap, unless waste is significantly reduced.
- Key assumptions in the modelling part of the EAT-*Lancet* Commission report result in an underestimation of impacts on planetary boundaries from seafood systems. Future development of the model should make sure that biodiversity impacts from capture fisheries and direct impacts from aquaculture are considered.
- The environmental footprints of both capture fisheries and aquaculture can vary significantly, depending on species and production/harvesting practices.
- Filling the anticipated future demand of seafood will require increased production, along with significant waste reduction (from harvest to plate), and a reduction in the environmental footprint of fisheries and aquaculture. This will necessitate a radical change in how seafood is produced and consumed and the governance structures influencing the extent to which seafood production is impacting planetary boundaries.
- In order to accurately translate the EAT-*Lancet* report to a blue food context, several knowledge gaps require to be filled. There is a need for a higher resolution of what different blue food diets would imply for planetary health, an expanded version of the EAT-*Lancet* food systems model, as well as more knowledge on how to achieve a blue food system transformation and increased resilience of fisheries and aquaculture in the future.

Box 1: Assumptions in the EAT-*Lancet* Commission food systems model of particular relevance for the seafood sector

The EAT-*Lancet* report's inclusion of environmental impacts and emissions from seafood production related *only to feed production for aquaculture*. This differs from earlier work on the environmental impacts of seafood production and consumption, where impacts were derived from a compilation of complete Life Cycle Assessment-results. The quantity of feed ingredients derived from agriculture was based on Troell et al[2]. This implies that the following was not included in the model:

- Greenhouse gas (GHG) emissions from capture fisheries
- Direct GHG emissions from aquaculture operations (farm level)
- Direct nutrient leakage (N&P) from aquaculture farms
- Impacts on biodiversity from capture fisheries (e.g. through over-harvesting, bycatches or destruction of habitats)
- Direct impacts on biodiversity from aquaculture farms (e.g. farm siting and effluents)
- Direct freshwater consumption and land use by aquaculture

Seafood in the EAT-*Lancet* Commission report

Given its health benefits, prospects for substantial expansion, and potential for a relatively small environmental footprint, the EAT-*Lancet* report suggests seafood to be a particularly promising source of protein in the future. Seafood is, however, a very broad food category with over thousands of species currently produced from capture fisheries and aquaculture. Production modes for the multitude of species, captured or farmed, are highly diverse, resulting in different environmental footprints and nutritional properties of products. Understanding how seafood can contribute to healthy and sustainable diets, without causing the transgression of identified boundaries, therefore requires an in-depth investigation of the seafood sector and its environmental impact, accounting for this noted diversity.

A key aim of this scoping report is to elaborate on the role of seafood in the future food system, including how the food system model applied by the EAT-*Lancet* Commission deals with seafood. For more information on general assumptions of the food systems model, see Box 1 and the EAT-*Lancet* report.

An advantage with the approach taken by the EAT-*Lancet* Commission and Springmann et al.[3] is that national and species relevant data (feed for aquaculture) was used for comparison of aquaculture systems globally. This is in contrast to earlier work, commonly averaging seafood product footprints from studies using varying methods and assumptions and mainly representing Western, highly industrial production systems. However, no direct impacts (farm level, local level) from aquaculture were included. Moreover, the capture fisheries sector also appears to have no environmental impacts at all, which is not the case.

This report constitutes a first step in outlining a holistic look at how seafood can contribute to healthy and sustainable diets. It does not provide in-depth analysis but outlines key academic areas that need to be considered for future studies to accurately translate the EAT-*Lancet* Commission to a seafood context, as well as identifies major gaps in scientific understanding. The report specifically identifies how seafood contributes to transgression of key planetary boundaries and, in turn, is influenced when different boundaries are approached. It also provides an overview of opportunities and challenges related to emerging game-changing seafood systems and technologies.

[*] "Seafood" generally refers to all edible aquatic animals and plants from both marine and freshwater environments, but is used in this report to refer to only aquatic animals

2. The contribution of seafood to human diets

Current patterns of consumption

In 2015, fish accounted for about 17% of animal protein, and 7% of all proteins, consumed by the global population.[4] Seafood provides a substantial part of daily animal protein intake for more than 3 billion people (ibid). However, seafood consumption differs markedly across the globe, with many developing countries consuming double the amount (per capita) than the least developed countries. Small-island developing states (SIDS) are among those consuming the highest levels of seafood per capita. This should however be interpreted in relation to limited supply, and high cost, of other sources of animal protein in these nations, and their overall (absolute) consumed volumes remain low compared to the rest of the world.

In regions that previously dominated fish consumption (such as Japan, the EU, North America), per capita consumption appears to have reached saturation, while consumption in Asia (excluding Japan) has steadily increased, driven by urbanization and rising incomes (driving increasing demand for higher valued species), and increased capacities for fish production, as well as increased international trade.[4]

Projected future seafood consumption in relation to EAT-*Lancet* recommendations

Based on recommendations of an average per capita daily consumption of 28g, the results from the food systems model run by the Commission show that shifting to the healthy reference diet will result in a substantial increase in demand for seafood. While a business as usual dietary scenario would lead to a need for a 48% production increase compared to 2010 levels, a transition to the healthy diet implies a required production increase of as much as 118%, while a scenario where food waste is halved would require a 60% increase. These figures need to be put in relation to currently available estimates of future production.

3. Seafood production – now and in the future

Current patterns of production

While capture fisheries remain a critical source of aquatic protein, 2013 marked the start of a new era in which the contribution of aquaculture to human seafood consumption exceeded wild-caught products for the first time. In 2015 farmed seafood contributed 53% of the seafood consumed globally.[4] Given the well-established scientific consensus on the state of the world's wild fish stocks[4], the proportion of aquaculture in fisheries supplies is projected to continue to rise.[4–6]

Since 1996 capture fisheries have seen a steady decline, and an overall decline in the marine global catch rate per unit effort, suggesting serious decline in the ocean's biomass.[7] Currently marine systems produce 87.2% of global catches and inland waters 12.8%.[4] Marine catch is dominated by ten nations, which together account for 60% of global marine catch, with China as the lead, closely followed by Indonesia, and the USA.

Currently, nearly 90% of aquaculture production is located in Asia, largely in China; while only approx. 1% is in Sub-Saharan Africa.[4] While China has been the world's largest aquaculture producer for a number of decades, and as such mostly satisfied their own nutritional needs with regards to fish, this may change due to environmental constraints now becoming apparent in China.[8] China's aquaculture growth rates have abated and their share in global aquaculture production has dropped 3% since the mid-nineties.[4]

Projections of future production

Multiple modelling exercises have been done to estimate future production from aquatic resources.[4,5,9–12] All show a further increase in seafood production. Most recent projections for 2030 rely on continued growth in aquaculture (approx. 30% compared to current levels) and stagnation of capture fisheries. Common across the projections is the assumption that growth will originate from South Asia, Southeast Asia and China. While these are useful as a tool to think about the future, they suffer from several limitations (see Box 2).

Most projections are done through extrapolations from the "business-as-usual" scenario (e.g.[5,9,10]). Such projections therefore do not include scope for radically shifting dynamics, such as changing diets, changing markets, novel technologies, changing fish stocks or environmental change. When discussing future production scenarios, it is also important to acknowledge that seafood production is highly diverse. First, it encompasses both aquaculture and capture fisheries, and within each of these sectors production modes vary greatly. From intensive high-input shrimp and salmon farming to low-intensity mussel farming in aquaculture; and from low bycatch and low fossil fuel pole and line fisheries, to benthic trawl fisheries with significant bycatch, collateral habitat damage and fossil fuel dependency. As such, capture fisheries and aquaculture differ in how they relate to the PBs. However, there are also important interconnections between the two sectors (e.g. capture fisheries providing inputs to aquaculture, and aquaculture sometimes impacting negatively on capture fisheries production); something that can have consequences for the overall seafood output and sustainability.[14,15]

It is important to put production projections, as those mentioned above, in perspective. We can do so by relating them to the 2050 seafood consumption figures emerging from the EAT-*Lancet* food system model. Assuming that capture fisheries will not increase further, and using available figures for projected aquaculture growth,[11] simple calculations (Box 3) show that only a healthy reference diet where we simultaneously halve our waste will be feasible, falling just within the range of what current aquaculture estimates deem realistic. A healthy diet which does not also limit waste will create a seafood overshoot of 78-93 Mmt. To understand the magnitude of this overshoot, it corresponds to roughly the entire current global capture fisheries yield.[4] A business-as-usual scenario will not put too much strain on the blue food production system, but is naturally detrimental to many other key planetary boundaries.

Societal strategies for securing enough seafood to feed a growing population in a healthy and sustainable way will clearly have to rely on many different strategies that differentially address the various constraints associated with the variety of production modes encompassed within seafood production as a whole. Below we outline some of these constraints as they relate to key planetary boundaries and governance of wild resources.

Box 2: Limitations of global seafood projections

1. A handful of complex, indicator-based models underpin the majority of seafood projections available today. While models are continuously tweaked and updated (e.g. Waite et al.[6] built upon Hall et al.[11]), it means system projections are all based on a very limited set of system representations.
2. Models rely on data and assumptions about causal relationships. The data available determines which indicators can be included in the models. Hence, the quality of the data and how accurately it captures real-world causal dynamics directly impacts the reliability of projections.
3. To model the dynamics of a system, assumptions about interactions between indicators are embedded into the models. Interactions within seafood markets, or within marine ecosystems, are quite well understood and documented. However, the mechanisms through which they affect each other are much less clear.[14]
4. To model interactions and arrive at projections, the models often use static environmental scenarios. As such, few environmental constraints (such as impacts of climate change or fishing pressure on stock development) are incorporated into the models.
5. Most projections are done through extrapolations from the business as usual scenario (e.g. [6,10,12]). Such projections therefore do not include scope for radically shifting dynamics, such as changing diets, changing markets, novel technologies, or changing fish stocks or environmental change.

Box 3. Calculations of the gap between projected seafood production and expected increase needed to meet different dietary scenarios in the EAT-*Lancet* food systems model

	Production estimates	2010 (a)	2050 Aquaculture production projection (low) (b)	2050 Aquaculture production projection (high) (b)
	Capture fisheries	89	90	90
	Aquaculture	59	140	155
	Total	148	230	245
	Projected production increase needed (c)	Total (Mmt)	Resulting production-consumption gap (overshoot)	
BAU (full waste)	48%	219	11	26
Healthy ref (½waste)	60%	237	-7	8
Healthy ref (full waste)	118%	323	-93	-78

(a) FAO 2010, State of the World's Fisheries and Aquaculture,[17] (b) Waite et al. 2014[5], (c) EAT-*Lancet* Commission report.[1]

4. Planetary Boundaries and seafood

Links between seafood production and planetary boundaries

Seafood constitutes an important part of the global food portfolio but its contribution and relationship to the various PBs has not been described in any coherent way (Fig 1). The limited treatment of seafood in the EAT-*Lancet* report results in the under-estimation of impacts from seafood. Compared to terrestrial farm animals, fish invest more of their metabolic energy into growth, as they neither waste energy on keeping temperature homeostasis, nor combating gravity. Both wild caught and farmed fish has therefore repeatedly been shown to out-compete many livestock in terms of environmental impacts.[5,18,19] Despite this, seafood production can nonetheless negatively affect many of the PBs.

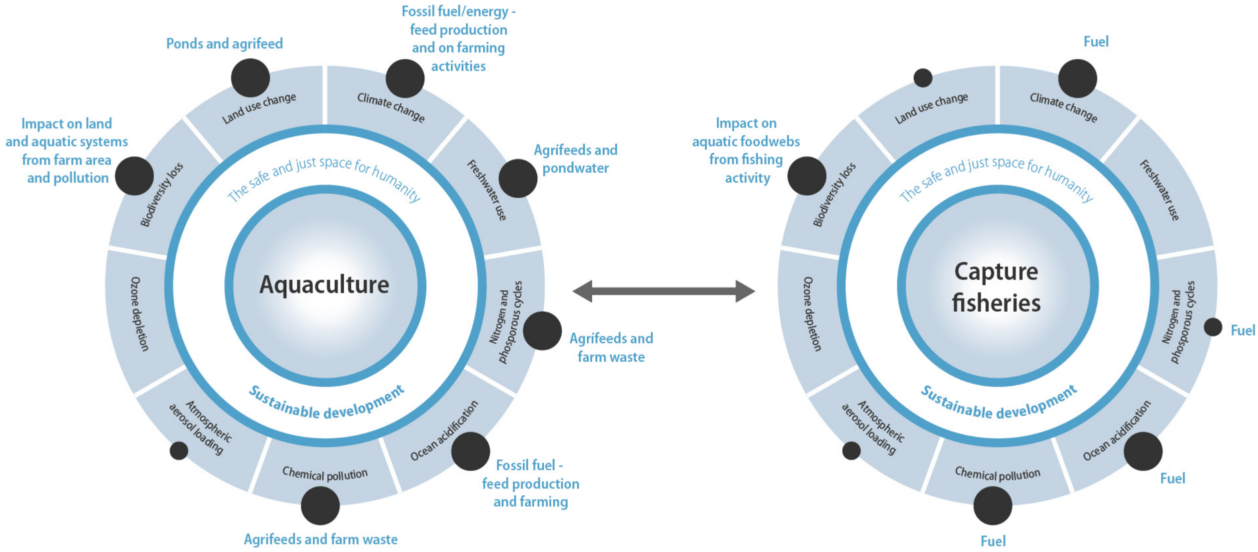

Fig 1. Schematic overview of how seafood, capture fisheries and aquaculture, relates to and contribute to impact on key planetary boundaries – some additional to the ones used in the EAT-*Lancet* report. Black circles illustrates where aquaculture and capture fisheries impact and sizes indicate degree of impact.

The environmental footprints of both capture fisheries and aquaculture can vary significantly. In aquaculture this is due to high diversity of farming systems, species, intensity, location and spatial scale of operations, and in capture fisheries as a result of diversity in target species and harvest methods (Troell et al. 2014, Hilborn et al., 2018, Parker et al., 2018). Life cycle assessment (LCA) is increasingly used to estimate one or several environmental impacts from seafood, generally including energy use, climate change, habitat change, pollution and exploitation of biotic resources (Fig 2).[5,18,22,23] While the environmental footprint of seafood production is obvious, it is noteworthy that approaching or crossing some of the PBs will also have serious consequences for the potential for seafood production, posing challenges for sustaining wild stocks and impeding aquaculture growth. These two-way impacts are outlined in more detail below.

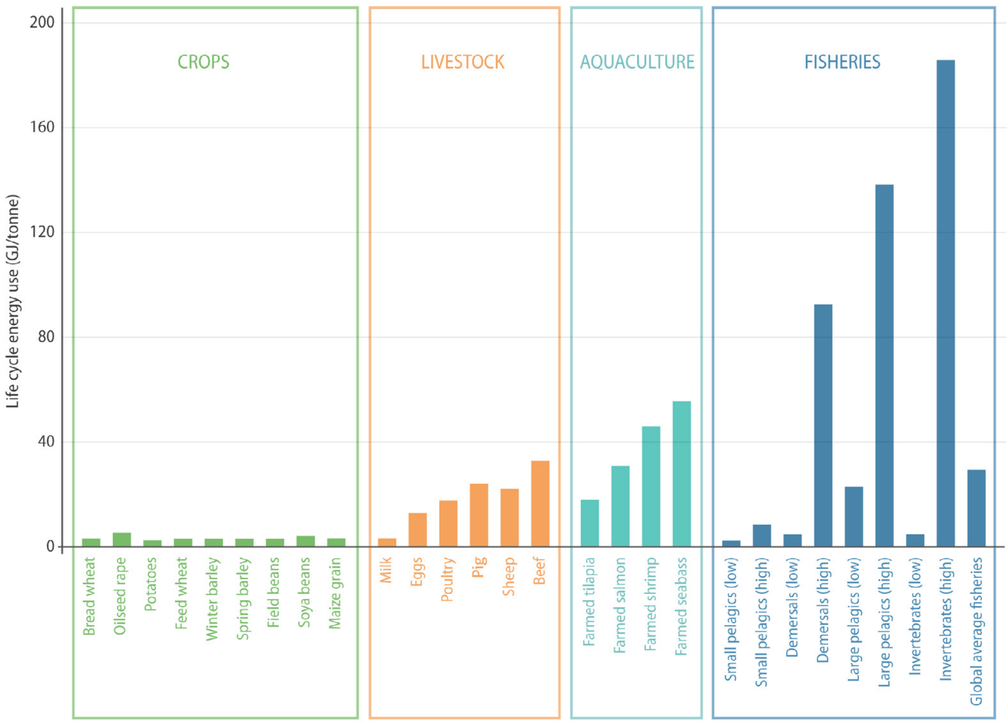

Fig 2. Cradle-to-producer gate life cycle energy use (GJ/tonne). Indicating large variability within capture fisheries and also that energy dependence can be significant in aquaculture. Note: Energy use correlates well with GHG emission except for livestock such as cattle and sheep where methane emission significantly increases GHG.[18]

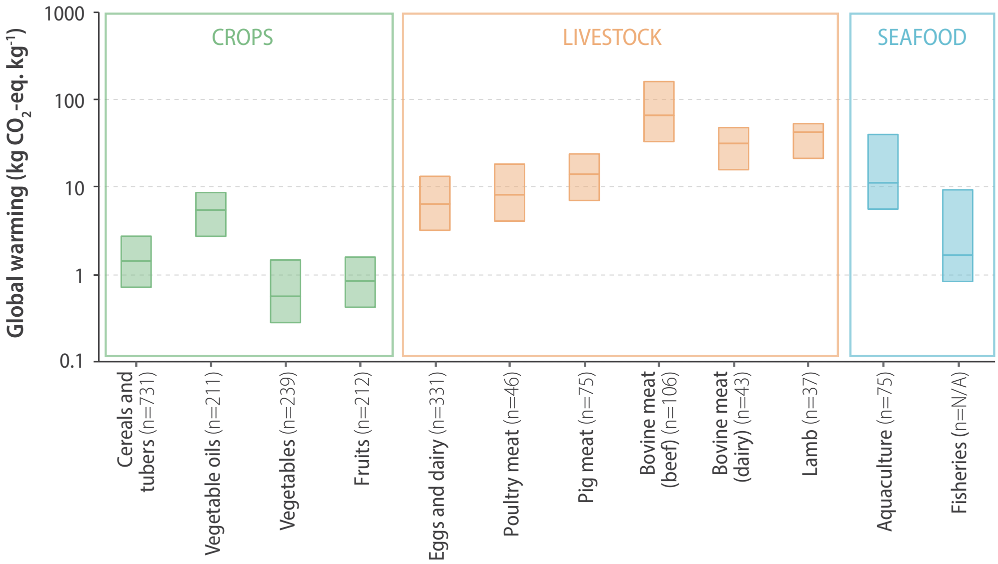

Fig 3. GHG emissions related to a kg of different food commodities from Poore and Nemecek,[27] and Parker et al.[21] Boxes indicate the mean and 10th and 90th percentiles and sample sizes are stated in the labels. Underrepresentation of systems due to missing LCA data is expected to be higher for aquaculture than terrestrial production systems, given the sector's diversity and the more limited number of LCA studies conducted.

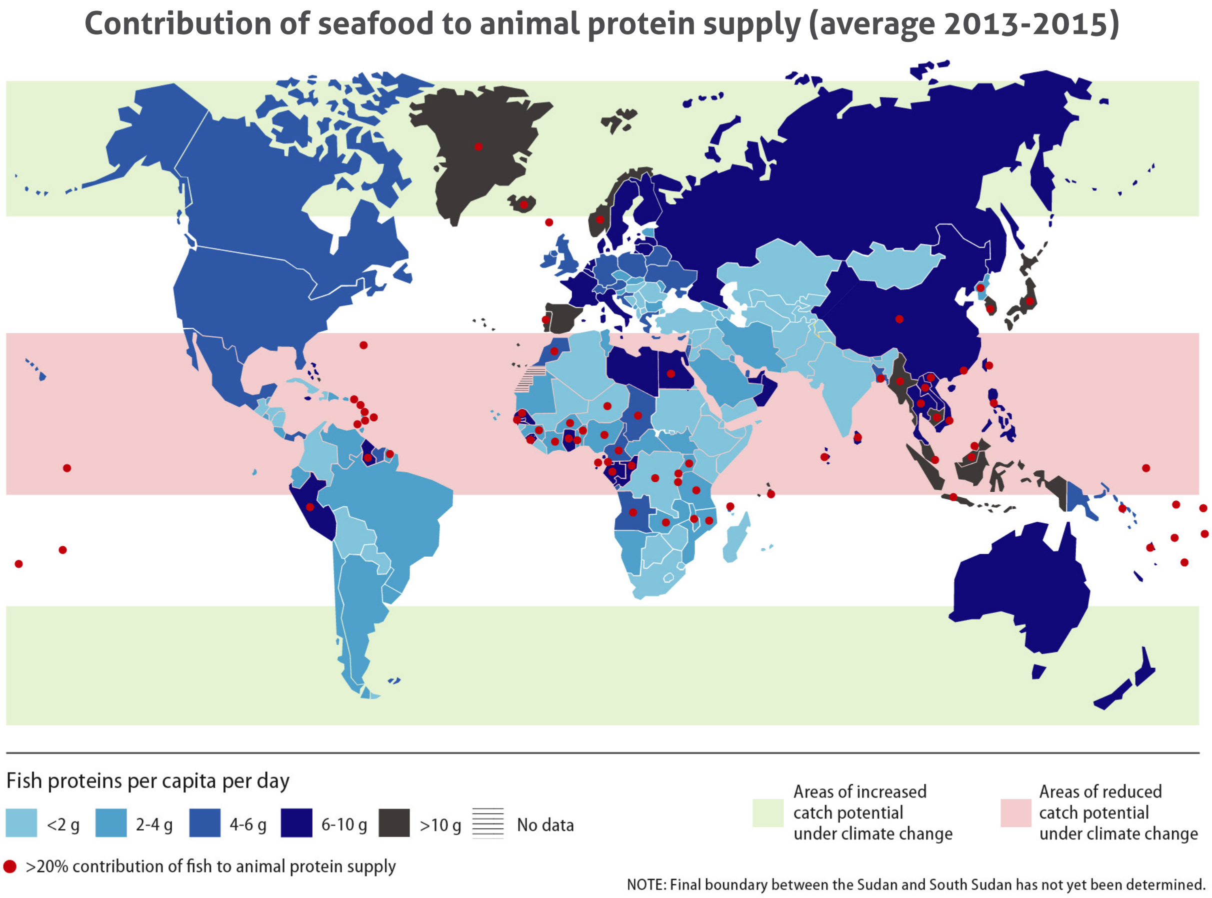

Fig 4. Map showing the contribution of seafood to animal protein supply across the world (adapted from FAO[4]). Overlain are the regions likely to experience increased and decreased catch potential (roughly adapted from Cheung et al. [33]).

Climate change

Release of GHG from capture fisheries mainly originate from fossil fuel use by fishing vessels.[21,24,25] The efficiency, i.e. release of GHG per catch, is defined mainly by catchability and fishing technology. Aquaculture's link to GHG emissions is more complex. Feed is the main contributor to GHG and this relates to both energy use for producing feed ingredients on land and from fishery resources (fishmeal and oil).[5,23] On-farm activities dependent on fossil fuel also add to GHG emission (Fig 2+3).[22,26]

In terms of impact on seafood production, climate change will most likely affect target species in capture fisheries through variations in oxygen concentration, temperature, acidification and toxicity of pollutants in aquatic environments.[28,29] Climate change will have effects both at the individual species level, as well as on the interactions between species and habitats, thus triggering geographic changes in species assemblages, but also changes in productivity and ecosystem resilience in both space and time (e.g. earlier spring blooms).[30,31] Contrary to most freshwater fish and invertebrates, who are restricted in their regional mobility, marine species respond to ocean warming by changing their distribution areas, usually shifting to higher latitudes and deeper waters.[29,32] Such shifts in marine species distribution are already visible and will provide a key governance challenge to tackle in the very near future. A modelling of the global capture potential for 1066 species of commercially exploited marine fish and invertebrates under various climate change scenarios[33] showed that climate change may lead to a large-scale redistribution of the overall catch potential, such that high-latitude regions will experience an average increase of 30 to 70%, while tropical areas are likely to experience decreased catches of up to 40%. This corresponds to a decreased catch potential in the regions currently most dependent on marine protein (Fig 4).

Aquaculture's future growth and net contribution will also be impacted by climate change. For many farmed species, even small temperature changes can have an impact on productivity. New disease and parasites may thrive under changing conditions, and heightened storminess (e.g., potential increase in frequency and strength of hurricanes and typhoons associated with climate change), can impact farm infrastructure.[34] Terrestrial aquaculture systems, like agriculture, will be vulnerable to projected shortages in freshwater availability.[34,35] All fed aquaculture will indirectly be impacted through its dependence on fishery resources and crop-based feeds.[2]

Land use

Capture fisheries have no direct impact on land use but supporting resources (e.g. energy) are in different ways related to land use transformations. Aquaculture on the other hand directly converts terrestrial areas to farming of aquatic organisms. A detailed estimate of global area of biomes converted to aquaculture, including on land, does not exist – only sporadic national statistics.[36] Land-based freshwater ponds make up 60% of global aquaculture production, while 10% represents shrimps and other crustaceans that are farmed mainly in coastal ponds. The rest of global aquaculture is produced in open-water (cages and ropes, in seas and in lakes) and therefore does not directly affect land use. Freshwater and brackish-water pond farming has driven large-scale local and regional landscape transformations. Rough estimates indicate that 110.000 – 130.000 square kilometers of freshwater ponds exist,[5,36] and additional 60.000 square kilometers of ecologically valuable coastal agricultural land and wetland habitats, mainly along the coasts of South China, India, Vietnam, Indonesia and Bangladesh, have been transformed and fragmented through land reclamation and conversion.

In 2016 almost 70% of cultured seafood was raised on supplemental feed inputs, and global use of fish meal and oil increased three-fold between 1992 and 2006.[37] Feed inputs are derived from agriculture, and as such directly relates to land use.[2] Thus, this dependency increases pressure on many different PB related to agriculture production. Of most significance is increased consumption of soy and corn, because these are also used for agriculture and human consumption, but the diversity of crops used as feed ingredients is large.[2,38] Farming of unfed fish species like filter feeding mollusks and carps continue to increase but at a slower rate than fed species.[4] In total, 24 million tonnes of unfed volumes were produced in 2016 and the marine aspect of this put no added pressure on land.

Freshwater

Few comprehensive analyses quantifying freshwater use for seafood production exist.[35,39] Freshwater use in capture fisheries is insignificant and relates almost entirely to post-harvest activities. In aquaculture water is used for agriculture feed resources, and in ponds. Freshwater use can be large for some pond-based aquaculture systems but varies greatly depending on system characteristics, location, and targeted species. An important aspect to consider is that some forms of aquaculture do not consume water but use it temporarily and release it back in somewhat degraded form (e.g. changing nutrient levels, toxicity and salinity).[35] This may have consequences for its further usability or for surrounding ecosystems. Extractive marine species like bivalves and other filtering organisms (and seaweeds) do not depend on freshwater for production. This makes them particularly important to consider for sustainability, from a water scarcity perspective.

Acidification

Both capture fisheries and aquaculture contribute to ocean acidification through direct use and indirect dependency on fossil energy. However, much more significant is effect of acidification on the capacity of ocean food production as pH changes. Ocean acidification (OA) has been identified as a substantial threat to marine ecosystems[40,41] although the degree and effects of OA are expected to be geographically heterogeneous due to regional differences in ocean circulation and chemistry.[42] Effects on ocean food webs will impact on fisheries production potential but also on aquaculture. Modelling efforts show that when accounting for ocean acidification the distribution and catchability of 120 species of fish and demersal invertebrates exploited in the North Atlantic are predicted to decline by 20 to 30% in comparison with simulations that do not take these disturbing factors into account.[43] A few cases exist in the USA where mussel and oysters have already been affected by acidification[44] but it is still too early to know how the aquaculture sector as a whole will fare. Different aquaculture species will face different challenges from acidification and controlled farm environments offer options for mitigating negative effects.[45] However, OA impacts on fisheries supplying feed ingredients, e.g. forage fisheries, will be very important for the aqua industry throughout the world.

Biodiversity

Capture fisheries and aquaculture both have significant effects on aquatic biodiversity. For aquaculture, impact constitutes both direct land and aquatic space conversion and effluents from farm operations released into surrounding habitats. The life cycles for most aquaculture species have been successfully closed but some species are still partially dependent on the capture of larvae from the wild. Through by-catch this generally impacts negatively on biodiversity.

For capture fisheries the impact is directly linked to extraction. While simplified, this impact can

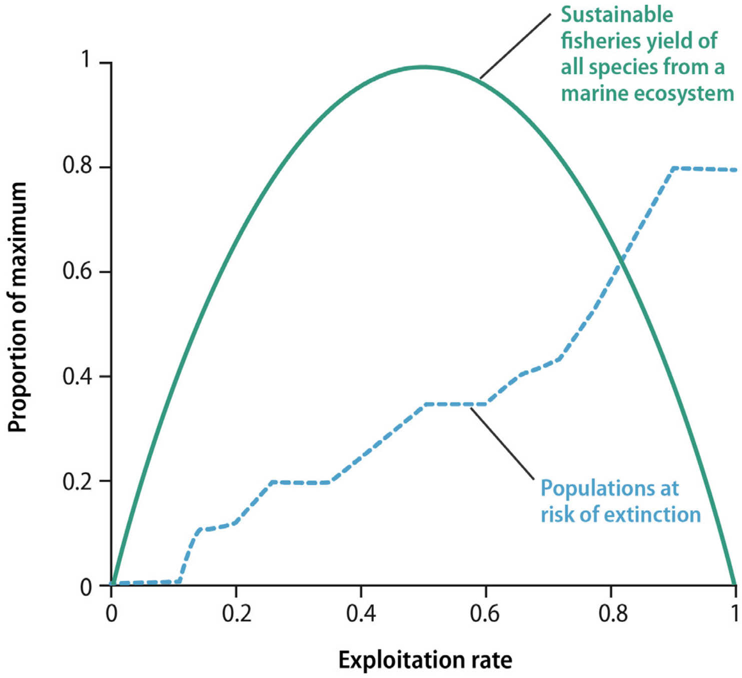

Fig 5. Visualization of the relationship between exploitation rate and biodiversity decline. Solid line represents the proportion of the maximum sustainable fisheries yield of all species from a marine ecosystem and the dashed line the proportion of populations at risk of extinction as a function of exploitation rate. Adapted from Brander[46], based on Worm et al.[47].

be visualized by showing how the proportion of populations at risk of extinction (measured as species richness) increases as exploitation rates increase (Fig 5).[46] Of course, species richness is only one aspect of biodiversity, but the graphic captures the broad scientific consensus that the objectives of simultaneously maximizing biodiversity and yields from fisheries are, to some degree, antagonistic.

How biodiversity impacts are manifested depends in capture fisheries on the species targeted and the modes of harvest. Broadly, impacts can be grouped into i) effects on individual species (population or stock); ii) biological communities; and iii) on entire ecosystems; as well as iv) biophysical disturbance to habitat.[48,49] At the species level, vulnerability to exploitation differs depending on life history and how easy a species is to catch.[50] Generally, large, long-lived species are more vulnerable to fishing pressure and many populations have been greatly reduced (or even wiped out) over time.[51–53] Apart from reducing abundance, fishing can also exert selective pressures that affect individual species by altering physiology and life history traits which, in turn, affect the functional role of the species within the biological community. Removal, extinction or drastic reduction in numbers of entire species (particularly apex predators) through extinction or drastic reduction in numbers, often changes predator-prey interactions, spilling over to change entire food web dynamics ([49,54] for review), and consequently affecting ecosystem functioning.[48] Such changes at the level of entire ecosystems are often referred to as regime shifts. A clear example of such a shift has been observed in the Northwest Atlantic where overfishing of cod led to marked increases in small planktivorous fish and predatory crustaceans, while no fish species has replaced the role of cod (or other groundfish), leaving the system with a seemingly permanently altered fish community, and the loss of an entire functional group. Similar shifts in ecological states have also been observed in other marine systems and in lakes.[55–57]

While not all fishing alters the physical habitat, gears such as bottom trawls do. There is growing evidence that seabed habitats throughout the world's oceans are being impacted by physical destruction or selective removal of habitat-forming species. As a result, seabed habitats are being homogenized, primarily by bottom trawling, which constitutes the main gear used for capturing various forms of flatfish, whitefish, and bottom dwelling crustaceans such as shrimps and certain crabs.[58,59]

New planetary boundaries related to blue food production

There have been calls for considering, in greater detail, the implications of existing PBs on ocean ecosystem functions.[60] Recently, plastic contamination has been suggested as a global threat to seafood, although science knows little about the consequences of this for seafood production at large.[61,62] Another seafood related boundary suggested is the development of microbial resistance through the use of antimicrobials.[63] Antimicrobials are commonly used in aquaculture, and resistance will affect all animal production and is also of key importance to human health.[64]

5. Seafood and human health

Seafood in the context of the EAT-*Lancet* report

The EAT-*Lancet* Commission report is clear about the health benefits of seafood. The suggested healthy reference diet consisted of 28 g of fish or shellfish per day (range 0-100g) which is about one or two servings per week. The unique role of seafood with respect to omega-3 fatty acids for specific groups, i.e. infants and pregnant women, was stressed. The net benefits of seafood inclusion in the diet will be determined by what else the diet consists of and if daily requirements of key macro and micro nutrients already have been reached. Some cautions were given related to the risk of toxic accumulation in some fish but even if one could avoid consuming such species many of the fatty fish with high concentrations of beneficial omega-3 fatty acids are the ones where toxins accumulate. The environmental impact model included different seafood types that were grouped into only a few groups; shellfish, fish (freshwater), fish (demersal), fish (pelagic). This simplification does not capture how species differ in nutritional qualities (and environmental impacts) – something that is important for knowing if a sufficient amount of seafood providing the required nutritional qualities will be available. For example omega-3 fatty acids comes from fatty fish and not from the bulk of seafood production which consists of more lean fish and shellfish species.

Nutritional qualities of seafood

It is clear that seafood plays an important role in fighting hunger and malnutrition throughout the world, especially for rural populations in many developing countries.[4,65] However, seafood is also increasingly important for contributing to healthy diets in developed countries. All seafood contains important protein and, depending on species, various amounts of fats and micronutrients (Figure FISHNUTRI).[4,66,67] Fatty and medium-fat fish are generally major dietary sources of omega-3 fatty acids and the relative levels and types of fatty acids differ from any agriculturally sourced food. But concentrations of polyunsaturated fatty acids, i.e. PUFA's, e.g. Eicosapentaenoic acid (EPA) and docosahexaenoic acid (DHA), also differ among seafood species.[66] Lean fish such as whitefish (cod, haddock, saithe and plaice, pike) contain relatively less compared to medium-fat fish (halibut, catfish, tuna) and fatty fish (herring, mackerel, trout, salmon, eel)[68] (Fig 7).

The generally high nutritional quality of seafood is not only related to sources of proteins and healthy fats, but also linked to a range of crucial essential micronutrients. Seafood is particularly rich in iodine, selenium, calcium, iron, zinc, vitamin D, vitamin A and vitamins B12 (Fig 6). However, the nutrient content differs between seafood species and the same species can vary in nutritional quality depending on fishing areas and seasons.[67] How the seafood is produced, processed, prepared and consumed also plays a role for nutrition quality.[67] Farmed fish and shrimps can have different nutrient profiles compared to wild caught. This stems primarily from the use of artificial feeds.[69] Small wild fish, eaten whole, brings additional nutritional benefits, as both skin and bones are generally consumed, and these are particularly important for many lower income individuals.[70,71] Finally, the nutritional quality is also affected by post-harvest handling, processing, transport and packaging. Seafood spoils faster than many other food groups if not chilled, making boiling or sun drying common and necessary preservation methods for seafood, but this reduces nutritional qualities - for vitamins up to 90% may be lost.[72]

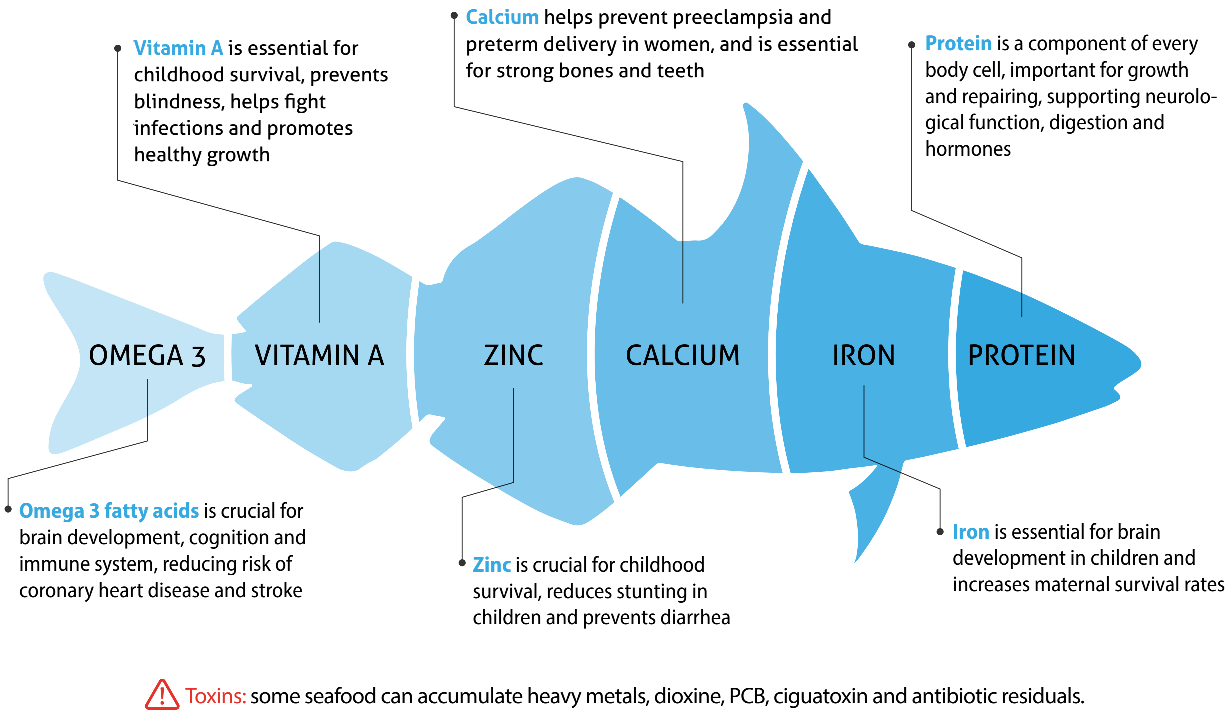

Fig 6. Fish provides important health benefits and remains an essential source of protein and micronutrients. Prevalence of high quality and easily accessible omega-3 fatty acids (DHA and EPA) has been identified as one of the main health advantages with seafood consumption. For some species caution should be taken due to accumulation of certain toxic compounds[66] .

Benefits for human health

Fish intake has been associated with reduced risk of cardiovascular disease (especially of myocardial infarction and stroke) and omega-3 fatty acids have an essential role as precursors of eicosanoids which regulates cardiac rhythm.[1] Nutritionally, seafood is particularly important for children and pregnant or lactating women, as it contributes to the neurodevelopment of unborn and young children's growth.[4,71] Fatty fish consumption has also been associated with reduced blood pressure as well as improved insulin sensitivity. There is also some evidence that fish consumption is related to reduced risks for type-2 diabetes, impaired cognitive function, and age-related macular degeneration. Studies indicate that dietary marine n-3 PUFA can be associated with reduced breast cancer risk,[1] and both fatty and some lean fish are good sources of dietary vitamin D. Global statistics obscure geographical and nutritional nuances associated with seafood.[67]

Risks with seafood

Fish and seafood can contain environmental toxins.[1,68] In general, fish captured in open seas have lower concentrations compared to fish from more enclosed waters. However, fish high up in the food chain can have substantial heavy metal levels due to bioconcentration (Figure 7).[68] For example, mercury concentrations are high in king mackerel, shark, swordfish, tuna, and tilefish. Therefore, this fish should generally be avoided by pregnant and lactating women due to negative neurological effects. Persistent organic pollutants (POPs) can also accumulate in seafood, with lean fish generally containing lower levels than fatty fish. Ciguatoxin (toxins from algal blooms) bioaccumulation is confined to herbivorous fish, especially on coral reefs, but can be a health hazard.[73] Farmed fish and shrimp can contain antibiotic residuals from use of antibiotics[64] which pose an indirect risk for human health from development of antimicrobial resistance. To date, no comprehensive overview exists of antibiotic use and resulting residuals in products within the aquaculture industry.[64] Effects on marine ecosystems from plastic pollution, and especially from micro plastics are still uncertain, but could potentially impact negatively on production from both capture fisheries and aquaculture and also human health.[61,62]

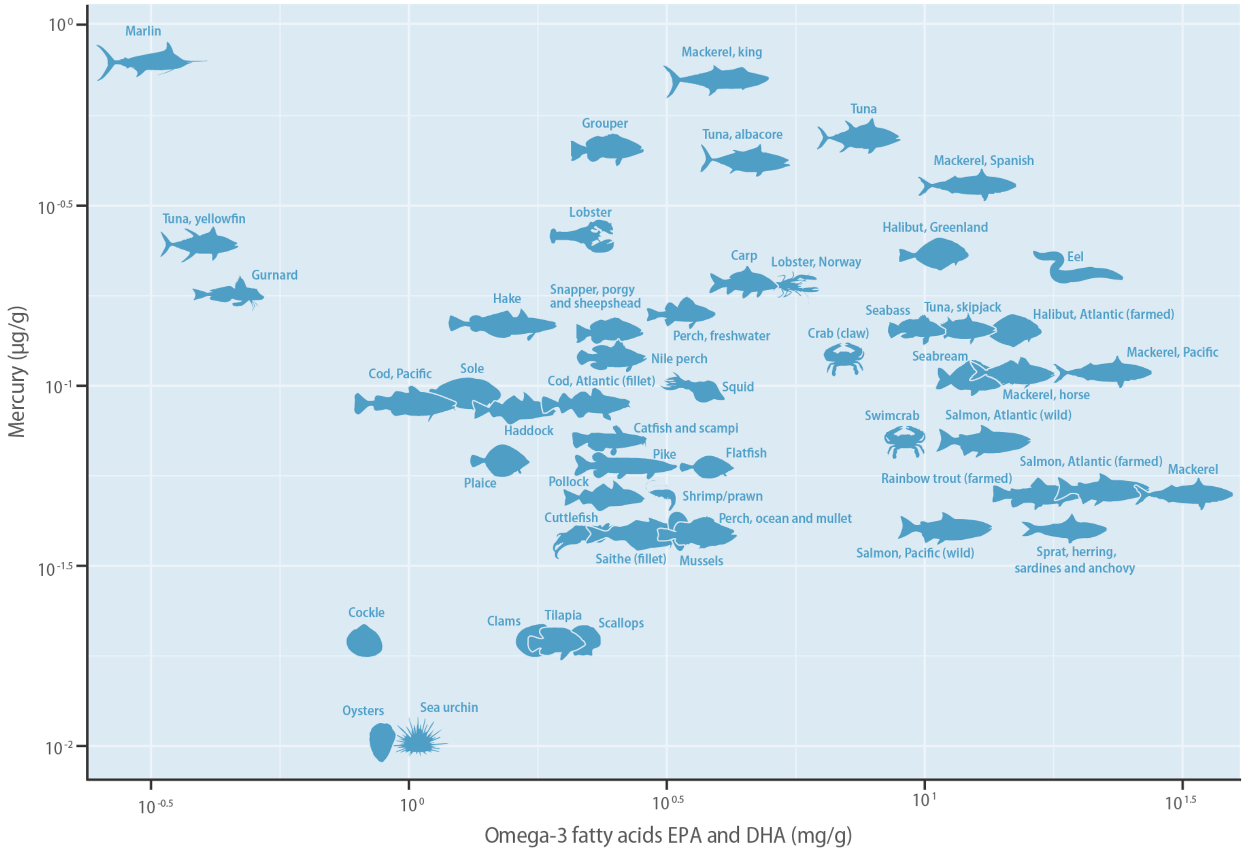

Fig 7. Illustration of omega-3 fatty acids and Mercury (Hg) in various seafood[68].

6. How to transform the global 'seafood system'?

Identifying key focal areas for improvement

In order to fill the future anticipated demand of seafood, increased production together with a reduction of the environmental footprint of fisheries and aquaculture will be necessary. To achieve this, there is a need for changes in how seafood is produced and consumed and the governance structures influencing the extent to which seafood production is impacting planetary boundaries.

An important feature of potential seafood game-changers is scalability, i.e. that the governance structures or systems/innovations/technologies can become mainstream in the future. Another relevant characteristic is the capacity to radically improve premises for increased production while maintaining or reducing the environmental footprint of the seafood sector. Identifying a potential game-changer is challenging as knowledge about environmental implications of novel management systems and technologies and their potential to make a sizeable contribution to world seafood production is largely missing or uncertain. Therefore, the following section primarily identifies focal areas in seafood systems where a transformation is urgently needed. For each area, a number of carefully selected measures/innovations are presented. The summary of systems and technologies should be regarded as a sample of some of the more promising alternatives, and not a full review of all interventions of relevance.

Box 4: Measures for improved food production practices

The EAT-*Lancet* Commission investigated whether a set of interventions (technological and management-related improved production practices, dietary change and reduced food waste) could enable food systems to stay within the scientific boundaries food systems (set by the Commission) by 2050. The model solely included measures feasible with existing technologies and not technological changes with high hypothetical advantages but currently far from implementation at scale.

In this report, both proven/commercial management systems technologies, and those currently at pilot scale, but with promising features, are summarized. This exercise could be considered a first step in identifying a portfolio of seafood production improvements to test in the future when the food system model is developed further.

Improving capture fisheries

Safeguarding wild fisheries resources through improved governance

Given its important contribution to blue food production (currently ~50% of total volumes), capture fisheries is a resource we cannot afford to lose. Improved governance for sustainable capture fisheries is therefore crucial. The opportunity lies in managing fisheries to achieve sustainable levels of fisheries yield, while maintaining levels of biodiversity that allow natural ecosystems to buffer both known but uncertain (climate change) and unknown environmental change.[16,74] Thus, minimizing biodiversity loss is generally understood as the safest way to secure well-functioning ecosystems and ensure the resilience of aquatic ecosystems to future environmental change. Oceans and lakes are heavily impacted by fishing, yet explicit strategies for how to minimize harmful impact, while increasing yields, remain underdeveloped. This constitutes a major governance challenge for blue food production in the future. A failure to sustainably manage wild stocks will increase pressure on many PBs, as wild capture products would have to be replaced through farming. The resultant increase in freshwater consumption means that consumption of captured marine species should actually be seen as a huge freshwater saving (sustaining global fish stocks equals a global water savings of about 5%).[75]

The Ecosystem Approach to Fisheries

There is broad scientific consensus that maintaining biodiversity is a key insurance mechanism to ensure sustainable capture fisheries, and to also mitigate negative effects of climate change on fisheries production.[76] The most widely cited path to maximizing production while maintaining biodiversity is the ecosystem approach to fisheries (EAF). EAF aims to reconcile exploitation and conservation of species to maintain the integrity and resilience of ecosystems. Striking such a balance is challenging, but studies of marine ecosystem responses and models of multispecies interactions provide a basis for such new ecosystem approaches.[46] There already exists a range of agreements relating to, or enabling, the implementation of EAF[77,78] and EAF as an integrated policy framework between fisheries and biodiversity is fully within the existing mandates of national and regional fisheries institutions so controversial mandate changes are not necessary.[79] As such, moving from policy framework to actual implementation of EAF across fisheries worldwide will be a game changer but appears to be hampered primarily by institutional capacity and political will. Other governance related hurdles to overcome to improve governance for sustainable capture fisheries are listed in Box 5.

Traceability of supply

The ability to accurately and reliably trace where and how seafood is harvested is fundamentally important to achieve sustainable governance and to ensure that no illegally caught products enter supply chains. Full-chain digital traceability uses electronic records and technology to track both forward movement of a product through the supply chain and backward history, including locations, and processing.[82] Two types of collaborations are necessary to achieve this. First, supply chain partners must agree to share some level of standardized data. Second, technology vendors must collaborate around supplying services and products within (and across) a specific supply chain so that their systems can effectively communicate and interpret this data, this is referred to as interoperability.[82] However, interoperability is currently almost non-existent in the seafood industry.[83] Significant efforts are being invested in blockchain technology to improve traceability, through the use of digital contracts and transparent, immutable record to pass on key information about the product. Development of unified standards for data reporting (so-called Key Data Elements) are also pursued industry-wide (see e.g. Global Dialogue on Seafood Traceability[84]).

Box 5. Additional hurdles to overcome to achieve improved governance for sustainable capture fisheries

The high institutional fragmentation at both national and international levels relating to fisheries and oceans remains a barrier to full implementation of EAF and other integrated approaches. Ridgeway and Rice[79] outline key areas around which enhanced collaboration and coordination can and should be pursued, including agenda and priority setting, norms and rules, and knowledge production for decision making and monitoring.

Harmful subsidies to the fishing industry have been on the fisheries governance agenda for decades, and remain a challenge. The enhanced fleet capacity tends to mask stock declines and economically and biologically unviable fisheries. It locks fisheries into overcapitalization and overfishing, exacerbated by the largely open access nature of many fisheries, in both EEZ and on the high seas.[80,81]

The organization and governance of seafood trade and markets plays a significant role in shaping harvest, use, and access to fish and is therefore an important part of a transition to sustainable fisheries and achieving food security and healthy diets.[66,81] The challenge is to ensure that trade policies are aligned to support policy objectives relating to sustainability of resource use and food security, including reviewing fisheries access agreements, tariffs on seafood products etc.

However, identified barriers impeding progress towards large-scale interoperability among digital traceability systems in the seafood sector include a competitive industry culture and discounted value of interoperability among industry actors, but also scarce resources for implementation. Interoperability can only succeed if all players in a supply chain engage, but today incompatibility between the multitude of electronic data systems used in the seafood industry presents a significant challenge, and are a barrier to tech vendors interoperating.[83] Full-chain digital traceability can be a game changer for our ability to achieve seafood sustainability. However, the barriers listed above, along with mechanisms to finance such efforts and alleviate some of the burden that interoperability places on particularly smaller seafood producers and processors, need to be urgently overcome.

Innovations in the harvest sector

While a host of new technologies that could improve monitoring, surveillance and harvesting exists, or are under development, it is unlikely that these will fundamentally transform governance or enhance production. These include drones and improved global navigation and positioning Systems (GNSS and GPS) which together with vessel identification (VMS or AIS) can show when a vessel is fishing and help detect illegal fishing.[85]

The majority of wild fish stocks is fully or over-exploited.[4] In some regions exploration of deep resources has therefore been proposed as means to increase yields but multiple factors speak against this as a game changer for increased production. To date, deep-seas contribute only a minor portion of the global catch (<0.5 %),[86] due to very high costs of extraction, but also low productivity linked to slow growing species and irregular recruitment. While technology can reduce costs, the vulnerability of stocks will not change,[87,88] and evidence suggests deep resources could easily and quickly be overexploited.[89,90]

Improving aquaculture

Implementing the Ecosystem Approach to Aquaculture (EAA) will be a key step for reducing the pressures on planetary boundaries, particularly on biodiversity, while maintaining ecosystem integrity and social-ecological resilience.[91] Also, in order to make sure that future aquaculture production does as much good for the most food-insecure people as possible, nutrition-sensitive production that takes the nutritional qualities of farmed seafood into consideration should be supported.[92] These core governance elements will be key for ensuring that healthy and sustainable seafood is produced in the future. In addition, it will be necessary to substantially increase production globally. However, high intensity production is commonly associated with increased environmental pressures, and thus needs to be dealt with for aquaculture to expand sustainably. A number of potential solutions or ways forward has been described in the literature (e.g. in a summary by Klinger and Naylor).[93] In the forthcoming section, focusing solely on measures to increase production sustainably, aquaculture innovations deemed to be both scalable and commercial/close to commercial are summarized.

Feed

Most aquaculture improvements/interventions can be found in the production step and processes further down the supply and production chain, e.g. feed manufacturing. In 2016, around 70% of all farmed seafood was dependent on feed, one of the main sources of environmental impacts from aquaculture (e.g. can account for more than 90 % of GHG emissions for cage farmed salmon).[94] Moreover, limited availability of marine feed ingredients due to declining or stagnating capture fisheries[14] and a growing demand for fish meal (FM) and oil (FO) from other food sectors constitute a barrier for further expansion.[95] Therefore, development of feed ingredients that can replace FM and FO will be (and has been) an important step for scaling up global production sustainably. Furthermore, it is crucial that the new feed is not influencing the nutritional characteristic of significance for human consumption in a negative manner and, ideally, not compete with ingredients that could be used directly for human consumption. Other important characteristics of new feed products are palatability for farmed animals and that the ingredients guarantee farmed animal health and stimulate growth. Earlier work has emphasized that innovations focusing on healthy FO replacements are particularly exciting as FM protein is easier to replace.[93,96]

New marine and terrestrial feed ingredients including *fish by-products* (seafood waste, cuttings and trimmings) from aquaculture and capture fisheries, krill, soy and rendered animal products are all commercial and, to some extent, scalable feed alternatives. In 2016, around 25–35% of FM and FO production stemmed from seafood by-products.[4] A challenge for upscaling the use is availability of ingredients with sufficient nutritional qualities for FM/FO, e.g. with respect to amino and fatty acids and minerals. Increased demand for quality by-products may increase value and stimulate a higher and unwanted fishing pressure. *Krill* constitute a minor portion of current aquaculture feeds but the demand is expected to increase. While krill meal has an appealing nutrient composition in line with FM/FO and is palatable, scalability is likely limited due to high costs and uncertain effects of fisheries on ecosystems and animals dependent on krill for feed.

Feed ingredients that possibly could be classified as future game changers, but are not yet are produced at any substantial level, include genetic and metabolic techniques to produce omega-3 fatty acids, microbes and other *single cell organisms* (SCO) and insects. Given that production of these innovative feeds still is at pilot level or producers just about to establish themselves on global markets, estimating the scalability and potential to transform the seafood system is challenging. SCOs hold great potential as aquaculture feed as they grow rapidly and can produce an extraordinarily high yield. The main obstacle for upscaling production is high costs, but also limited knowledge of physiological effects on farmed animals.[97] Insect meals have been described as less promising than SCOs due to their less advantageous nutritional profile and ability to be produce in high yield. However, there is, as previously mentioned, a great uncertainty about the potential of these feeds and more knowledge needed on how to stimulate implementation at scale.

To conclude, it is unlikely that one single new or innovative feed source could fill the demand from the growing aquaculture sector. Instead, future aquaculture feed will likely be composed of a combination of terrestrial, marine and more innovative feeds, including SCO and insects.

Systems

Innovations specifically targeting the design of production systems is another area where new technologies could make a difference. *Recirculating Aquaculture Systems* (RAS) are more or less closed production units where the water exchange is limited. A key advantage is that they can be placed anywhere, thus far from e.g. sensitive coastal habitats and tropical fast-growing species can be produced in regions with temperate climate. Water consumption is sometimes also reduced, as well as spread of nutrients and diseases. On the downside, recirculating systems generally consume large amounts of energy, leading to a large product carbon footprint. Also, these systems are commonly located in developed, Western countries and are often expensive and technically advanced and the extent to which this technology is even imaginable for small-scale producers in Asia must be questioned. Similar to RAS, *aquaponic systems* are (semi) closed circulating systems but also connect the nutrient rich wastewater with hydroponics to produce plants for human consumption.[93] The main obstacle for upscaling is challenges in creating optimal growth conditions for all organisms (fish, bacteria, plants) and therefore most commercial operations are currently of small scale. Other barriers include costs for operation and that systems often require large land areas.[93] For both RAS and aquaponics, the environmental footprint would be substantially reduced if low-carbon or renewable energy sources were used.[5]

Integrated multi trophic aquaculture (IMTA) often implies co-cultivation of fed aquaculture species together with lower trophic, extractive (e.g. mussels) and autotroph (plants) species absorbing feed and nutrients not consumed by the fed animals.[98] IMTA systems can, if carefully designed, reduce nutrient loads and thereby lower the risk of eutrophication (ecosystem response to fertilization). Today only few large commercial examples of IMTA systems exist, although some giant coastal areas with multiple species exist in China.[99] There is a potential risk of disease transmittance between co-cultured species and unpredictable ocean currents may limit optimal nutrient uptake.[99,100]

Moving aquaculture operations offshore, i.e. far out in open water, is another approach to reduce impacts related to spread of excess nutrients and diseases in ecologically sensitive coastal areas. Though the definition of *offshore aquaculture* is somewhat unclear,[99,101] it generally implies aquaculture operations positioned far from the coast and often at high depth.[93] While these systems have potential to improve farm performance, concerns have been raised regarding negative effects on benthic habitats and spread of diseases and genes to wild populations.[102] Also, most offshore and IMTA systems include species reliant on conventional feed, implying that they alone likely not will be game changing technologies pushing the aquaculture industry towards sustainability.[6]

Species

Breeding programmes aimed to increase the effectiveness of animals in converting feed to human food is likely one of the most promising area when it comes to aquaculture innovations. Only 10% of current aquaculture production has been part of a breeding programme[5] and while substantial sums has been invested in salmon farming, carp, the largest aquaculture species group by volume, has been subject to few breeding efforts. In 2010, only 10% of existing programs focused on carp, constituting around 40% (by weight) of world aquaculture production, seaweeds excluded. Risks associated with breeding programs include spread of unwanted genetic material to wild populations.[93]

Shifting seafood production towards lower trophic species could also improve the potential of seafood production to scale up and constitute food for a growing world population. Currently, 30% of aquaculture production is "non-fed" species (mostly carps and bivalves), seaweed excluded.[4] While not a specific focus of this report, seaweed (macro-algae) constitute an additional product that potentially could be consumed (directly or indirectly) in a higher extent in the future (see Box 6). A general trend in Asian aquaculture is a shift away from low trophic species less dependent on feed of animal origin, to carnivorous species such as shrimp, grouper and salmon.[103] Important to note, however, is that while these species generally have a larger environmental footprint, particularly when it comes to feed related impacts, the general mode of highly intensive farming also implies advantages in the form of less land acquired to sustain production.

Diseases

Diseases and parasite outbreaks are more prevalent in intensive systems and while improvements in

Box 6. More green on the seafood plate? The role of seaweed for human consumption

Production of aquatic marine plants has increased rapidly, from 13.5 – 30 million tonnes (1996-2016) led by China and Indonesia[4]. Recent expansion has focused on tropical seaweed species used for carrageenan extraction, but also seaweed species used for direct human consumption. Seaweed's potential for making a substantial contribution to global foods has lately been stressed,[105] given their good nutritional qualities (proteins, omega 3 and micronutrients) and low environmental footprint.[106,107] However, to what extent they can shift from being a nutritional supplement to become a staple for carbohydrates, fatty acids and protein is unclear.[105] Even so, FAO[108] estimated that almost 38% of the 23.8 million tons of seaweeds in the 2012 global harvest was eaten by humans in forms recognizable to them as seaweeds (e.g., kelps, nori/laver), not counting additional consumption of hydrocolloids (e.g., agars, alginates, carrageenan) used as thickening agents. Seaweeds generally contain much less EPA or DHA than animals, but do provide some omega-3 in the optimal forms and also contains useful amounts of zinc, iron B6 and B12. It is clear that there is substantial evidence for algae as nutritional and functional foods, yet there remain considerable challenges in quantifying these benefits, and in assessing potential adverse effects.

management has been made, outbreaks still remain an important barrier for aquaculture expansion and continue to cause major loss of harvest (and thereby waste of natural resources) and economic value.[109] Moreover, conventional strategies for combating disease outbreaks can have negative environmental and social consequences, e.g. spread of anti-parasite chemicals and pathogens resistant to antibiotics. Besides implementing better management practices and innovative production systems, e.g. RAS reducing spread of disease, new diagnostic technologies and vaccines constitute promising interventions for risk reduction. Vaccinating farmed animals have been common practice in the salmon industry for decades, but have not yet been successfully spread to other species groups or the Asian continent. Development of new innovative diagnostic technologies could also reduce risk. Artificial intelligence (AI) can foster general improvements in farm performance. One example from the salmon industry, though still at the experimental stage, is sensor chambers identifying and treating individual fish for certain diseases and sea lice infections, reducing the need for treatment of a whole cage.[110]

It is highly uncertain whether existing technologies will be scalable enough to positively transform the growth and environmental footprint of the

Table 1 Overview of interventions and systems that could help transform aquaculture systems to improved environmental sustainability.[88,93–95,100–102]

	Innovation	Benefits/potentials	Barriers/considerations
Feed	Rendered animal products	Economically available	Limited nutritional value Food safety concerns
	Fish by-products	Available Relatively good nutritional value	Limited nutritional value
	Krill	High nutritional value Palatable	Energy intensive Likely effects on ecosystems High price
	Microbes, including micro-algae	Relatively high nutritional value High potential yield	High production cost Unclear effects on fed animals
	Insects	Relatively high nutritional value. Can grow on food waste	High cost Limited scalability and nutritional qualities Unclear effects on fed animals
	GM techniques	Could reduce need for other Omega-3 sources	Concerns from public about GM-crops Cost?
Systems	RAS	Closed systems with little or no emissions or land requirements	Energy demanding FM/FO in feed
	Aquaponics	See RAS Diversified production	See RAS Challenging to scale up
	IMTA	Reduced emissions Diversified production	Risk of disease transmittance between species Challenging to optimize nutrient uptake, FM/FO in feed
	Offshore aquaculture	Reduce risk of spread of diseases Little or no emissions or land requirements	Capital intensive, high tech FM/FO in feed
Species	Selective breeding	Increased growth, disease resistance	Relatively high cost
	GMO	Increased growth & resistance to disease	Risk of spreading genetic material Public concerns
Disease	Mix of interventions	Reduce risk for disease outbreaks Limited use of antibiotics and chemicals	Challenging to implement for certain species & systems, particularly small scale

aquaculture sector by 2050. An important aspect is uptake and availability of technologies among small scale producers in Asia, now accounting for approximately 80 % of global production.[66] Making central tools, feeds and technologies available and affordable for small-scale aquaculture farmers is therefore crucial. With most of the most promising and innovative techniques still in their infancy (e.g. SCO feed), the benefits for global seafood systems remains to be seen. However, it is most likely that no single measure or innovation will function as a silver bullet resolving all environmental challenges. Rather, it is more likely that a portfolio of more and less effective interventions will function as a "game changer family".

Reducing fish consumption generally in the wealthy and well-nourished parts of the world (see also Jacquet et al.[104]) will also likely be important for reducing environmental pressures.

7. Future research needs

In order to understand scientific targets for healthy diets and sustainable food systems from an ocean and seafood perspective, an in-depth aquatic food assessment is needed.

The following broad areas are suggested for future research:

The seafood plate – impacts of different pescetarian diets

Improve the understanding of what different pescetarian diets mean for human health and planetary boundaries. For instance, what would the health and environmental implications be if salmon and tuna (much preferred species in the western hemisphere) are replaced with mussels, algae and low trophic species such as carp?

Blue foods in food system models

There is a need to develop the model used by the EAT-*Lancet* Commission to better include all impacts from both aquaculture and capture fisheries. This would imply:

- Investigate the need for additional planetary boundaries of relevance for seafood systems
- Include all direct impacts from aquaculture, including land and water use and emissions of nitrogen and phosphorous.
- Construct different scenarios of decarbonisation of society, impacting on e.g. GHG emissions from fisheries.
- Explore how effects on biodiversity from seafood production could be better captured in the food systems model. This applies to direct impacts from aquaculture operations (e.g. siting in sensitive areas), but particularly to capture fisheries appearing to have no impacts on biodiversity in the current model.

Resilience and transformation of global seafood systems

- Deepen the knowledge of emerging/looming threats to the quality of seafood, e.g. microplastics, AMR and how seafood production systems could adapt to avoid risk.
- Increase the understanding of the realistic potential of innovative systems and techniques, quantification of their benefits and also outline how to accelerate promising products and systems.
- Explore how to best transform seafood production systems to sustainability and expand current production in a sustainable and nutrition sensitive manner. Suggest specific governance strategies for seafood depending on outcome from the food systems model.
- Investigate what the projected impacts of climate change are on our abilities to meet the projected demand (based on the healthy and sustainable diet). Both marine fisheries production (better modelled to date) and inland freshwaters (much less modelled, but will be crucial for African countries who will experience large population increase and where inclusion of fish could really have big impacts on health) would need to be considered.

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