Commissioned by

HIGH LEVEL PANEL *for*
A SUSTAINABLE
OCEAN ECONOMY

BLUE PAPER

The Future of Food from the Sea

LEAD AUTHORS

Christopher Costello, Ling Cao and Stefan Gelcich

CONTRIBUTORS:

Miguel Angel Cisneros, Christopher M. Free, Halley E. Froehlich, Elsa Galarza, Christopher D. Golden, Gakushi Ishimura, Ilan Macadam-Somer, Jason Maier, Tracey Mangin, Michael C. Melnychuk, Masanori Miyahara, Carryn de Moor, Rosamond Naylor, Linda Nøstbakken, Elena Ojea, Erin O'Reilly, Giacomo Chato Osio, Ana M. Parma, Fabian Pina Amargos, Andrew J. Plantinga, Albert Tacon and Shakuntala H. Thilsted

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About this Paper

Established in September 2018, the High Level Panel for a Sustainable Ocean Economy (HLP) is a unique initiative of 14 serving heads of government committed to catalysing bold, pragmatic solutions for ocean health and wealth that support the Sustainable Development Goals (SDGs) and build a better future for people and the planet. By working with governments, experts and stakeholders from around the world, the High Level Panel aims to develop a roadmap for rapidly transitioning to a sustainable ocean economy, and to trigger, amplify and accelerate responsive action worldwide.

The Panel consists of the presidents or prime ministers of Australia, Canada, Chile, Fiji, Ghana, Indonesia, Jamaica, Japan, Kenya, Mexico, Namibia, Norway, Palau and Portugal, and is supported by an Expert Group, Advisory Network and Secretariat that assist with analytical work, communications and stakeholder engagement. The Secretariat is based at World Resources Institute.

The High Level Panel has commissioned a series of 'Blue Papers' to explore pressing challenges at the nexus of the ocean and the economy. These Blue Papers summarise the latest science, and state-of-the-art thinking about innovative ocean solutions in technology, policy, governance and finance realms that can help to accelerate a move into a more sustainable and prosperous relationship with the ocean. This paper is part of a series of 16 papers to be published between November 2019 and June 2020. It considers the status and future trends of food production through capture fisheries and mariculture at regional and global scales; the opportunities of ocean-based food in achieving Sustainable Development Goal 2 (Zero Hunger); and identifies opportunities for action to transition to more sustainable and abundant food production from the ocean. While the HLP supports the general thrust of the findings and opportunities for action, members have not been asked to formally endorse the Blue Papers, and should not be taken as having done so.

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Foreword

The High Level Panel for a Sustainable Ocean Economy (HLP) commissioned us, the co-chairs of the HLP Expert Group, a global group of over 70 content experts, to organize and edit a series of 'Blue Papers' to explore pressing challenges at the nexus of the ocean and the economy. The HLP identified 16 specific topics for which it sought a synthesis of knowledge and opportunities for action. In response, we convened 16 teams of global content experts. Each resulting Blue Paper was independently peer-reviewed and revised accordingly. The final Blue Papers summarise the latest science and state-of-the-art thinking on how technology, policy, governance and finance can be applied to help accelerate a more sustainable and prosperous relationship with the ocean, one that balances production with protection to achieve prosperity for all, while mitigating climate change.

Each Blue Paper offers a robust scientific basis for the work of the HLP. Together they will form the basis for an integrated report to be delivered to the HLP. In turn, the HLP intends to produce a set of politically endorsed recommendations for action in 2020.

Here we present the first Blue Paper. How we feed a growing global population in a way that is nutritious, sustainable and economically viable is an increasing challenge. This Blue Paper confirms the importance of ocean food production systems in global future food and nutritional security. It offers a dual message of urgency and hope. Through smarter management of wild fisheries and the sustainable development of marine aquaculture (mariculture), the ocean could supply over six times more food than it does today, while helping restore the health of ocean ecosystems. This is a remarkable finding that should spur responsive action from governments, financial institutions and business.

Looking to the ocean as a source of protein produced using low-carbon methodologies will be critical for food security, nutrition and economic stability, especially in coastal countries where hunger and malnutrition are a challenge. Yet these advances in ocean production can only be achieved with a concurrent focus on addressing threats to ocean health, such as climate change and overfishing.

As co-chairs of the HLP Expert Group, we wish to warmly thank the authors, the reviewers and the Secretariat at the World Resources Institute for supporting this analysis.

We thank the members of the HLP for their vision in commissioning this analysis. We hope they and other parties act on the opportunities identified in this paper.

Hon. Jane Lubchenco, Ph.D.
Oregon State University

Professor Peter Haugan, Ph.D.
Institute of Marine Research, Norway

Hon. Mari Elka Pangestu, Ph.D.
University of Indonesia

Key Messages

- The ocean plays an important role in global food provision and has the potential to play a much more significant role through increased mariculture (i.e. aquaculture that occurs in the sea) production, and to a lesser extent, traditional capture fisheries production.
- Improved management and judicious conservation of exploited wild fisheries result in more biomass in the ocean, higher profits for fishers and an increase in food provision (over 40 percent more production compared to future production under 'business as usual' and 20 percent more than what is currently produced).
- The major threat to improved capture fisheries outcomes is overfishing, which is driven by illegal fishing, capacity-enhancing subsidies, a lack of alternative livelihoods, a lack of incentives to protect the underlying resource, poor local and institutional governance and less than optimal management. Other important threats include climate change, environmental variability, habitat degradation and pollution.
- Sustainably expanding unfed mariculture (i.e. mariculture of species that do not depend on feed inputs for nutrition, such as bivalves and seaweed) can substantially increase nutritious food and feed with a lower impact on the marine environment, and may in some cases enhance wild fisheries by creating artificial habitats.
- Significantly expanding fed mariculture (i.e. mariculture of species that rely on feed inputs for nutrition, such as finfish and crustaceans) in a sustainable way is possible but will require major innovations in feed so production is not limited by capture fisheries.
- Under optimistic projections regarding alternative mariculture feed innovations and uptake, the ocean could supply over six times more food than it does today (364 million metric tons of animal protein). This represents more than two-thirds of the edible meat that the FAO estimates will be needed to feed the future global population.
- While the supply of food from the sea can expand significantly, demand for these products will depend on prices, consumer preferences, income and national and local capacities to implement novel management approaches.
- Low-income and food-deficit countries, as defined by FAO, depend more heavily on fish for their animal protein. Fish are particularly important in small island developing states in tropical regions, which are most vulnerable to climate change and suffer from weak fishery management and unsustainable mariculture development. Improving fisheries management and mariculture sustainability can pay large dividends to these countries in the form of food from the sea.
- The potential for increased production and consumption of food from the sea will depend on physical factors (such as ocean warming and pollution), policy (such as fishery and climate policy), technology (such as advances in aquaculture feed and offshore mariculture technology and farming systems) and institutions (such as property rights and trade).
- While some policy interventions can result in win-win situations, many policies that enhance ocean food provision come with trade-offs. Policymakers should carefully consider the pros and cons associated with different policy options, including inaction, and how different stakeholders may be affected by them.
- Effective policy interventions regarding the future of food from the sea will vary by country depending on each country's objectives and constraints. Therefore, there is not a one-size-fits-all policy for enhancing food from the sea. We outline a framework that policymakers and scientists can use to inform regional decision-making regarding the future of food from the sea given their unique contexts.

1. Introduction

Fish[1] and plant production from the sea has increased over time, providing an important food source for many across the globe (Figure 1). Fish play an important role in global food provision, accounting for about 20 percent of animal protein and 6.7 percent of all protein consumed by humans (FAO 2018, 2016). This number is even higher in some developing regions such as Indonesia, Sri Lanka and many small island developing states, which derive 50 percent or more of their animal protein from aquatic foods (FAO 2018). The ocean contributes a major portion of the world's fish products, with ocean-based production representing nearly 90 percent of global landings from capture fisheries and about a third of aquaculture production (FAO 2018). As the global population and people's incomes rise, the demand for ocean-derived food will continue to grow. By some estimates, nearly 500 million metric tons (mmt) of animal meat will be required to feed the global population in 2050 (FAO 2018, 2009)—food from the sea has a large potential to meet this need. At the same time, hunger and malnutrition continues to be a challenge in many countries, particularly in rural or developing areas (FAO 2018; UNDP n.d.). To help address this, one of the United Nations Development Programme's Sustainable Development Goals (SDGs) is to end all forms of hunger and malnutrition by 2030 (UNDP n.d.).

We argue that for five key reasons, the ocean can play a unique role in contributing to sustainable food security, where the term food security encompasses concepts of food production, nutrition and accessibility.

- **Climate change:** Food production contributes to climate change. However, food production from the sea may be advantageous from a climate change perspective for three reasons. First, because their production occurs in the ocean, capture and mariculture production do not directly drive land conversion like land-based food systems (e.g. conversion from forests to farms and areas for raising livestock)[2]. Second, for many marine species, the greenhouse gas emissions associated with their production are comparatively low (Hoegh-Guldberg et al. 2019). A recent study indicates that greenhouse gas emissions per portion of protein associated with the production of large pelagic, small pelagic and white fish capture fisheries, as well as the production of molluscs and salmon in mariculture, are lower compared to terrestrial animal production (Hilborn et al. 2018).

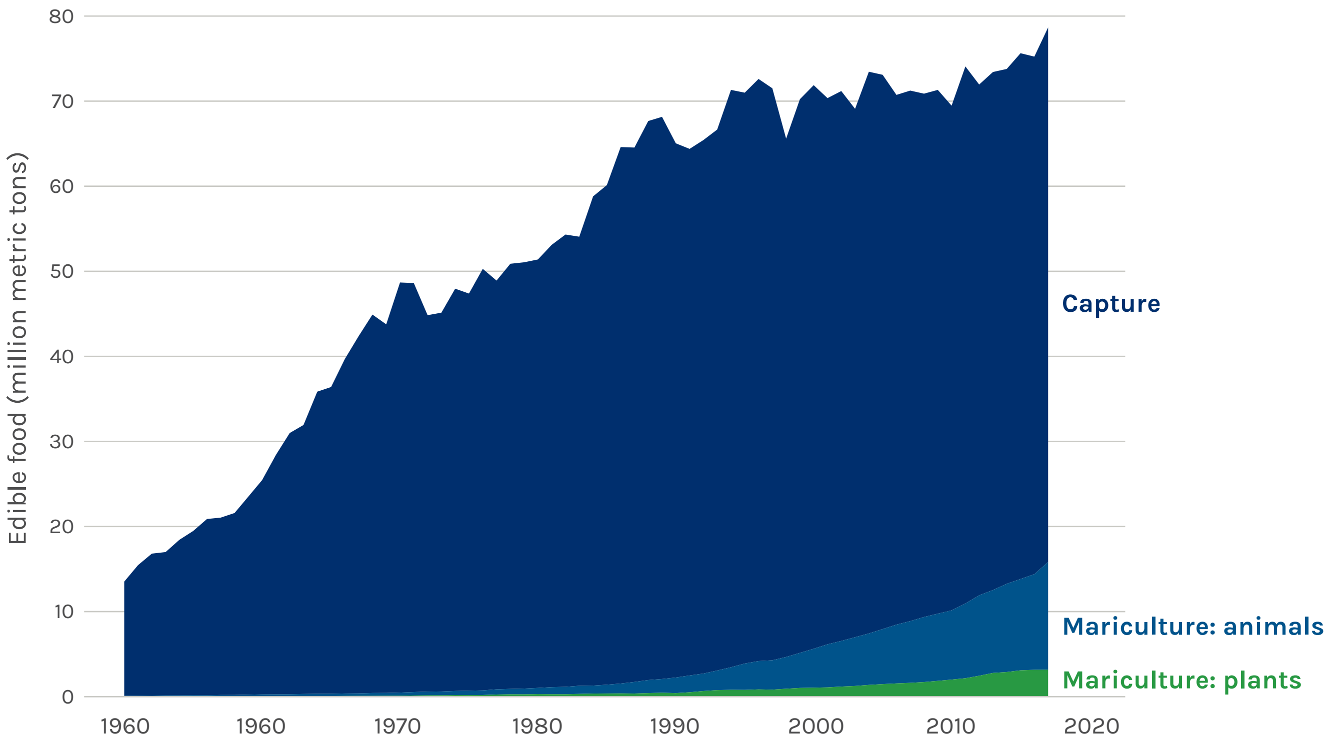
- **Feed efficiency:** Ocean animals are particularly efficient in converting feed into food for humans. Fed mariculture production systems convert feed much more efficiently than terrestrial production systems (Huntington and Hasan 2009; Hall et al. 2011), and unfed mariculture systems do not require feed inputs.

- **Production potential:** Unlike land-based food production, the suitable area for cultivating food from the sea is not limited by scarce land and water resources. Relevant limitations in the sea include competing sectors, coastal circulation, depth and nutrient availability.

1. In this paper, we adopt FAO's definition of fish (fish, crustaceans, molluscs and other aquatic animals, excluding mammals, reptiles, as well as seaweeds and other aquatic plants).

2. It is important to note that fed mariculture that relies on terrestrial crops as feed ingredients may indirectly contribute to land conversion. See Section 3 for a more detailed discussion about fed mariculture ingredients.

Figure 1. Historical Production of Marine Capture Fisheries and Mariculture over Time



Note: This figure shows food potential, as it does not take into account historical non-food use.

Source: Production data are from FAO (2019). Landed quantities are converted into million metric tons of edible food equivalents using conversion values from Edwards et al. (2019) and Duarte et al. (2017).

- **Nutrition:** In addition to protein, food from the sea provides essential vitamins, minerals, long chain omega-3 fatty acids and other nutrients not found in plant-source foods or other animal proteins (Kawarazuka and Béné 2010; Allison et al. 2013; Golden et al. 2016). These nutrients are essential for cognitive development and particularly important for children, pregnant women and nursing mothers. Micronutrients such as vitamin B12 are limiting nutrients in the diets of many households and critical for preventing micronutrient deficiencies (malnutrition) (FAO 2018). A recent study finds that nutrients in the wild marine finfish caught in some countries exceed dietary requirements and thus could play an important role in addressing existing malnutrition (Hicks et al. 2019).

- **Accessibility:** Food from the sea is readily available to most coastal populations, and trade plays an important role in moving ocean food products around the world. In regions that are most dependent on seafood[3] for consumption, food from the sea is affordable and often preferred over other animal food sources (FAO 2018), and recent research shows that seafood plays an important role in nutrition provision for low-income countries in Africa and Asia (Tacon and Metian 2018). Increasing production of both wild and farmed fish will continue to decrease prices, improving accessibility (FAO 2018).

Despite seafood's importance in current diets and highly nutritious content, studies that examine the role that sustainably derived seafood could play in the future of human diets are limited. A recent review report prepared by SAPEA (2017) found that the ocean has the potential to contribute more food through improved management of existing capture fisheries, development of unutilised and underutilised wild fish stocks and expansion of mariculture activity. The SAPEA report, as well as Duarte et al. (2009), finds that the greatest food potential comes from the mariculture of low-trophic, and thus highly food-efficient marine organisms, including macroalgae and filter-feeders. Until recently, the potential for seafood to contribute significantly to food security has been largely missing from relevant political discussions and regional development strategies (Allison et al. 2013).

The purpose of this Blue Paper is to examine the role that the ocean can play in providing sustainable food from the sea, which will depend on both the supply of and demand for seafood products in the future. We draw from existing literature from many fields and perform a novel analysis to provide insights on this topic. We focus on two main sectors: (1) established capture fisheries and (2) mariculture, and further differentiate between unfed mariculture (e.g. seaweed and filter-feeders) and fed mariculture (e.g. finfish and crustaceans). Freshwater aquaculture is excluded from this report as it is outside the scope of food potential from the sea. In each section, we report on current status and trends, production potential, and threats to future production. We then derive and analyse the supply curve of seafood from capture fisheries, bivalve mariculture and finfish mariculture, which displays the amount of seafood that is produced at a given price. Because finfish mariculture production depends on feed inputs, we provide scenarios that represent a range of assumptions regarding future feed formulas and availability. Next, we discuss past and projected trends for seafood demand, which help assess the likely uptake of seafood into the human diet. We then identify potential barriers and challenges, including important environmental consequences, associated with increasing production of food from the sea, as well as relevant trade-offs. We conclude by identifying opportunities for action.

Food from the sea provides essential vitamins, minerals, long chain omega-3 fatty acids and other nutrients not found in plant-source foods or other proteins

3. Unless noted, we use the term seafood to represent food from the sea.

2. Capture Fisheries

2.1 Current Status and Trends

Current production from established marine capture fisheries[4] (industrial and artisanal) represents a significant portion of total food fish production but has remained stagnant at 80 million metric tons (mmt)[5] for three decades. The majority of capture fishery harvest is directly consumed by humans. The remainder is directed to non-food or indirect food uses, such as the production of fishmeal and fish oil (FM/FO), which are mainly used as feed ingredients for aquaculture, livestock and pet food (Cashion 2016). While the global catch of wild fish has been nearly constant for three decades, potential annual production is actually higher than the current level, but attaining this higher production will require improvements in fishery management. Global production levels cannot be sustained under current fishing pressures. Future production potential is discussed in the following section.

The health of a fish stock is crucial for determining its current and future contribution to food. A fish stock is considered healthy when the underlying biomass is near that which can produce maximum sustainable yield (MSY) on average over time. When biomass B equals B_{MSY}, the stock is theoretically able to produce MSY. F_{MSY} is the fishing mortality rate that maintains an average biomass level at B_{MSY}. Overfishing occurs when the fishing mortality rate is greater than F_{MSY}.

When a fish stock is managed with biomass near B_{MSY} and fishing pressure near F_{MSY}, the fishery theoretically returns an annual catch of about MSY. In other words, such a fishery is being managed to maximise long-term food production. Short-run increases in food production are possible from such a fishery, simply by fishing harder (so that $F > F_{MSY}$). However, such increases in food will be short-lived because the eventual decrease in biomass will, in the long run, decrease food provision. Therefore, managing fisheries for MSY targets is crucial to maximising long-term food production. This implies that by examining the current status of a fishery, we can assess the opportunity to expand food provision by improving its management.

While most assessed fish stocks are considered healthy, the majority of fish stocks in the world are unassessed, and therefore their status is uncertain. The status of global fisheries is well understood for only about half of the global fish catch. Recent studies conclude that the majority of *assessed* fish stocks are in a healthy condition (FAO 2018; Costello et al. 2012, 2016; Ricard et al. 2012; Hilborn and Ovando 2014). Assessed stocks tend to be the much larger, industrial-scale fisheries in the developed world (FAO 2018) and are often the fisheries that garner the most management attention.

Even in data-rich contexts, such as with formal assessments, it can be difficult to accurately determine MSY targets and stock status in capture fisheries because of complex social, environmental and ecological interactions that are challenging to incorporate in stock assessments. In addition, abiotic forces can have a stronger influence on stock status (e.g. through environmentally driven recruitment) than, for example, managing the resource by fishing at F_{MSY}. This becomes even more complicated for fisheries that lack formal stock assessments—in other words, for the majority of fisheries in the world. Using data-poor approaches, the majority of unassessed fisheries are estimated to be overexploited (biomass is $< B_{MSY}$) and experiencing overfishing (current fishing pressure $> F_{MSY}$) (Costello et al. 2016), suggesting there is room for improvement in providing food from these fisheries. Small-scale fisheries may currently play an important role in regional food security and nutrient provision, or have the potential to

4. Unless otherwise noted, this section focuses on “traditional” capture fisheries, or those that are already established. We discuss the potential for under- and unexploited marine resources to contribute to global food supply later in this section but do not include these stocks in our analysis because of data limitations.

5. All production volumes are reported as live weight equivalent unless specified otherwise.

do so, which highlights the importance of these fisheries despite their being largely unassessed.

Fishery management can be used to influence fishing pressure and can be a powerful tool for curbing overfishing, allowing depleted stocks to recover and promoting sustainable extraction. While many large industrial fisheries have transitioned to strong forms of management in recent years (Worm et al. 2009), most fisheries around the world are small, coastal fisheries that are either unregulated or loosely regulated, often because of a lack of institutional and/or technical capacity (Costello et al. 2016). This context often leads to open-access equilibrium, where users exploit the resource to a point at which the biomass level becomes unhealthy and profits are depleted to below or near zero (hence the need to subsidise them). Harvest of a given fishery resource in this open-access, overexploited state is typically significantly lower than it could be by maintaining fish populations at their most productive sizes.

In many developed and some developing countries, fisheries have turned a corner toward sustainable use. Anderson et al. (2019) describe the main management approaches currently employed to manage fisheries, including limiting catch, limiting effort and controlling spatial access. Within these three broad categories, a number of tools and restrictions can be used to achieve a variety of outcomes, including food security, economic and biological states. Management implementation has helped rebuild fish stocks, for example by using total allowable catch (TAC) limits in tuna and billfish stocks (Pons et al. 2017). Although managed fisheries tend to be large and industrial-scale, examples of fishery reforms in small-scale fisheries (e.g. in Mexico and Chile) suggest that while appropriate management interventions may be context-specific, reform is possible across a range of fishery types (Worm et al. 2009; Gelcich et al. 2010; Gómez-Lobo et al. 2011; Finkbeiner and Basurto 2015).

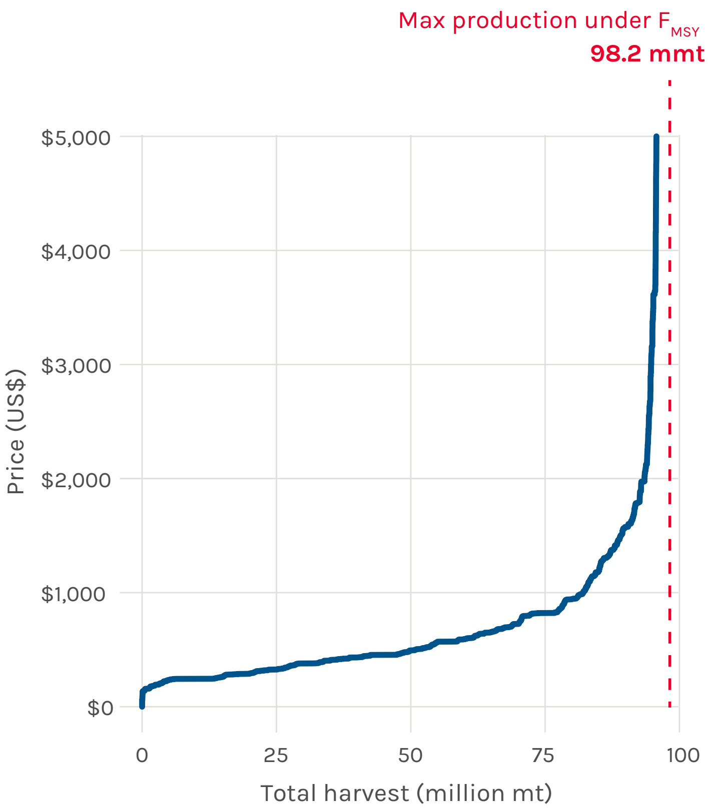
2.2 Future Production Potential

The world's fisheries currently extract about 80 mmt of reported fish landings per year from the ocean; unreported or illegal catches are discussed below. If we continue with 'business as usual' fishing pressure in the world's fisheries, we can expect reported fish catch to level out at about 67 mmt per year because of overfishing on some stocks and underfishing on others (Costello et al. n.d.). Future production of capture fisheries around the world will be limited by biological and ecological constraints, as well as by how people interact with fish populations (Sumaila et al. 2012; Kelleher et al. 2009; Ye et al. 2013; Costello et al. 2016). But what could be possible if we improved management?

Improving management by reducing overfishing, using catches more efficiently and increasing production from underfished resources could increase catches to 98 mmt (Costello et al. n.d.). This is 20 percent more fish catch than we currently obtain and over 40 percent more than projected future catch under current fishing pressure (FAO 2018). Emerging research discussed later in this report suggests that when management costs and the price of fish products are also considered, maximum economically viable sustainable production is around 96 mmt in steady-state (slightly lower than biological maximum sustainable yield) (Figure 2). While these gains may seem impressive, they represent relatively small increases in global food production (global animal food production is near 400 mmt). Thus, while fishery management plays an important role in sustainability, the gains in global food from sustainable fisheries management are likely to be modest.

These results are based on single-species models of fishery production. The implications of fishery production may be different if we explicitly consider species interactions. For example, the removal of predatory fish may increase the abundance of smaller fish, possibly resulting in an overall greater food production by volume (Szuwalski et al. 2017). It is also important to consider that in order for overfished fish stocks to rebuild, fishing pressure will likely need to be temporarily reduced or suspended, impacting employment and short-term food provision.

Figure 2. Estimated Supply Curve of Capture Fishery Production in Future Steady State Accounting for Fishing Cost, Management Cost and the Price of Fish



Source: Supply curve estimates are from Costello et al. (n.d).

A number of unexploited or underexploited marine resources, if properly managed, could contribute to long-term food production. Examples of these resources include zooplankton, krill and mesopelagic fish (i.e. those that inhabit intermediate depths of the ocean, 200–1,000 meters below the surface). Zooplankton and krill are currently harvested in small quantities and used in aquaculture feeds, pharmaceutical products, supplements, and as bait. Mesopelagic resources are currently unexploited, but they could represent a substantial amount of biomass, although estimates are uncertain due to challenges associated with sampling and acoustic measurements (Kaartvedt et al. 2012; Irigoien et al. 2014; SAPEA 2017). Increased demand for fish oils for use in feed and the anticipated need for more food production have renewed interest in exploiting these marine resources (Tiller 2008; St. John et al. 2016). However, the extraction of these resources may have important implications for biodiversity, existing fisheries, food web dynamics and oceanic carbon sequestration (SAPEA 2017). More research is needed to determine how these resources could be sustainably extracted and their potential to contribute meaningfully to food production given preferences.

2.3 Threats to Production

Overfishing[6]

Nearly a third of assessed and many unassessed fisheries are overfished (FAO 2018; Costello et al. 2016). Overfishing ultimately reduces stock abundance below the level needed to produce MSY, which results in lower fish catch and compromises food security. Industrial, small-scale or artisanal and recreational fisheries can all contribute to overfishing, and factors such as overcapitalisation may encourage overfishing. Studies suggest that ending overfishing could result in over 90 mmt of annual harvest, which is substantially greater than current production and what is achievable in the future under a business as usual scenario (Ye et al. 2013; Costello et al. 2016). Overfishing is driven by a number of factors, including a lack of alternative livelihoods; fishing capacity-enhancing subsidies (see below); illegal, unregulated and unreported (IUU) fishing (see below); and a lack of incentives or governance to protect the underlying resource. Socially equitable rights-based fisheries management, which assigns a property right to extraction or to given areas of the ocean, has the potential to align economic and cultural incentives with environmental stewardship.

Illegal, unregulated and unreported fishing

IUU fishing can result in decreased abundance and catch due to overfishing and increased uncertainty in stock assessments, resulting in misinformed management guidelines. IUU fishing results in 11–26 mmt of catch annually, which represents about 20

6. There are three kinds of overfishing: growth, recruitment and habitat. Growth overfishing occurs when harvested fish are on average smaller than the size at which they would produce maximum yield per recruit. Recruitment overfishing occurs when harvest depletes the mature adult population and therefore reduces the number of offspring. Habitat overfishing occurs when habitat or ecosystem alteration affects production potential.

percent of reported global catch (Agnew et al. 2009; Cabral et al. 2018). In addition, discards of unwanted bycatch species and undersized individuals, although difficult to measure, have been estimated at 9.1 mmt globally (Pérez Roda et al. 2019). Even fisheries that are relatively well managed can decline when subject to illegal and other unreported fishing activity, including unregulated or unreported subsistence catch, discards and recreational harvest (Pauly and Zeller 2016; Arlinghaus et al. 2019). Unaccounted fishing effort and catch can increase uncertainty in stock assessments and status estimates, particularly if the level of misreporting is not constant (Rudd and Branch 2017). In this setting, deriving appropriate management targets is even more challenging than usual (Agnew et al. 2009). The extent of the IUU problem is widespread, contributing to stock declines and in some cases collapse in industrial and small-scale fisheries, high- and low-value fisheries, and fisheries in both developed and developing nations (Safina and Klinger 2008; Field et al. 2009; Öztürk 2013; Varkey et al. 2010; Sumaila et al. 2004).

Political will is an important factor in addressing IUU fishing, as governments will need to establish and enforce strong fishing legislation. One fishing policy aimed at reducing IUU fishing is the Agreement on Port State Measures to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing (PSMA), which sets standards for vessels using ports and may increase monitoring via inspections (FAO 2018). Another more controversial strategy for combatting illegal fishing is Indonesia's recent policy of confiscating and destroying illegal foreign fishing vessels, which has resulted in the sinking of over 300 vessels and a more than 25 percent decrease in overall fishing effort (Cabral et al. 2018). For more information on IUU fishing, see Blue Paper on "IUU Fishing and Associated Drivers".

Capacity-enhancing subsidies

Capacity-enhancing subsidies may result in overfishing and thus reduce potential food production. Capacity-enhancing subsidies in the fishing sector are direct and indirect financial transfers, usually from the government, that reduce fishing costs, increase catch or raise fishing revenues. Unless subsidised fisheries are tightly regulated, these subsidies provide a financial incentive for fishers to fish longer, harder and farther from port, which can compromise fish stock productivity and food provision. Estimates of total annual global fishery subsidies (capacity-enhancing and other forms of subsidies) range from US$14 billion to $54 billion (Milazzo 1998; Christy 1993; Sumaila et al. 2016), representing around 35 percent of all global fishing costs.

Capacity-enhancing subsidies contribute to overcapitalisation and incentivise overfishing (Sumaila et al. 2010). A recent study found that without subsidies, over half of the fishing grounds located in the high-seas appear to be unprofitable at current fishing levels (Sala et al. 2018). In fisheries that lack accurate and effective management controls to limit overall catch, such investments may lead to overfishing and thus lower long-term harvest. Redirecting funding from capacity-enhancing subsidies to beneficial subsidies, such as investment in management and fishery assessments, may reduce overfishing and contribute to the long-term sustainability and conservation of ocean resources. To the extent that subsidies drive stocks to an overfished state, removing these subsidies will increase food provision. For more information about ocean subsidies, see Blue Paper on "Ocean Finance".

Climate change

Moderate climate change[7] is not expected to dramatically alter the global production potential of fish, but regional implications may be significant, with losses concentrated in tropical latitudes. Several recent papers have estimated the future effects of climate change on fishery production potential. Climate change is expected to alter fish productivity (affecting how many fish can be sustainably caught) and spatial ranges of fish populations (affecting who can access them). However, model forecasts generally find that under most Representative Concentration Pathway (RCP)[8] projections, global catch potential does not change dramatically (-5 percent to +1 percent) (Cheung et al. 2010; Gaines et al. 2018). These moderate global changes mask often large fishery-level changes, where species-specific and regional changes can be substantial (Merino et al. 2012; Blanchard et al. 2012; Barange et

7. RCPs 2.6, 4.5 and 6.0.

8. Representative Concentration Pathways are the greenhouse gas concentration projections used by the fifth Assessment Report of the Intergovernmental Panel on Climate Change. Each pathway describes a climate future based on greenhouse gas emission scenarios.

al. 2014; Lam et al. 2016; Gaines et al. 2018). Individual species may experience negative, neutral or positive responses to climate change. For example, a recent study finds that some species may experience up to a 35 percent increase in MSY, while others are expected to essentially go extinct (Gaines et al. 2018). Free et al. (2019) estimate that ocean warming has already decreased total MSY for 235 of the world's largest commercial fisheries by 4.1 percent (1.4 mmt).

Similarly, spatial shifts have already been observed for a number of commercially important fish stocks (Pinsky et al. 2013). Regionally, most species are expected to shift into new nations or completely out of nations by the end of the century (Gaines et al. 2018). Countries in high-latitude regions are expected to benefit from climate change (projected 30–70 percent increase in fish catch potential), while tropical nations are expected to experience the greatest losses (projected 40 percent decrease in fish catch potential) (Barange et al. 2014, 2018; Cheung et al. 2010). Fishing activity in high-latitude regions will be affected by not only increased production but also increased accessibility due to the melting of ice at the poles. As these areas become more accessible, pressure on resources and the surrounding environment will be at risk of overexploitation and degradation by multiple sectors (e.g. fisheries, shipping). International coordination will be an important tool for minimising negative impacts from this transition—in October 2018, 10 nations signed the Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean (CAO), which prohibits unregulated fishing in the high seas areas of the central Arctic Ocean for 16 years and creates a joint program for scientific research and monitoring (NOAA Fisheries 2018). The livelihoods of coastal communities and indigenous peoples in tropical regions, especially in small island states and territories, are frequently very dependent on capture fisheries for essential nutrients, subsistence and their local economies (Golden et al. 2016; Finkbeiner et al. 2018; Bellemare et al. 2013; Hanich et al. 2018). They should be treated as the most vulnerable in terms of food security.

Shifts across management jurisdictions can create challenges for existing management institutions, so international cooperation through strong transboundary institutions will be necessary to protect shifting fish populations (Bindoff et al. 2019; Gaines et al. 2018).

Regional fisheries management organisations and other international coordination arrangements may offer strategies for effective management of multinational stocks, and may be increasingly important for managing shifting stocks in the future. For more information about how climate change is expected to impact fishery indicators, see Blue Paper on "The Expected Impacts of Climate Change on the Ocean Economy".

Interactions with fed aquaculture

Mariculture could negatively affect capture fishery productivity and thus catch potential. Most mariculture takes place within a few kilometres of shore. But because this also happens to be a very productive location for wild fisheries, spatial conflicts can arise. Potential direct impacts to capture fisheries include disease transfer and genetic pollution from escaped fish (which in extreme cases may result in the extinction of a wild population) (Clavelle et al. 2019). Mariculture operations can indirectly affect capture fisheries through reduced water quality due to chemical and nutrient pollution from inputs and waste, habitat modification or destruction and the introduction of invasive species (Clavelle et al. 2019). Both unfed and fed mariculture can negatively affect the marine environment, highlighting the importance of farming design and techniques.

In addition, fed aquaculture (freshwater and marine) still relies on large amounts of wild-caught fish, particularly forage fish (e.g. anchovies and sardines), as a critical feed input for production. Forage fish play an important role in marine ecosystems, as they feed on plankton and transfer energy from lower trophic levels to the seabirds, marine mammals and larger fish that feed on them. Without healthy forage fish populations, marine food webs and habitats could be severely altered. Thus, forage fisheries must be carefully managed to avoid overexploitation given the demand for feed from the aquaculture industry.

Habitat degradation and pollution

Habitat degradation and pollution caused by activity within and outside the fishery sector can negatively affect fish abundance and fishery outcomes, which impact food safety and security. Some habitats are critical for particular stages in fish development (e.g. spawning habitats), while others sustain fish by providing food or shelter for the majority of their lives (e.g. reef species depend on reef habitats). Pollution can directly and indirectly reduce capture fishery production through increased egg or larval mortality, decreased recruitment and habitat degradation (Shahidul and Tanaka 2004). Mariculture operations, if not carefully maintained, can result in chemical and nutrient pollution. Because both capture and mariculture fisheries are affected by habitat degradation and pollution, we discuss the relevant implications together in Section 7.6.

2.4 Management Tools

Fishery management can be designed to achieve a number of objectives, many of which are consistent with enhancing food provision. There is a rich literature on the management interventions employed in fisheries (see Anderson et al. 2019). We find that many of these approaches are motivated by outcomes other than food provision, such as promoting livelihoods or increasing economic benefits. Table 1 outlines some of the pros and cons (or challenges) associated with different fisheries management approaches and interventions for food provision purposes. Management tools are not mutually exclusive, and using multiple tools together may address challenges posed by using individual approaches in isolation. Technical and institutional capacity and governance at the local and national levels are key to the successful design and implementation of effective, innovative and adaptive management practices (see Section 7.1 for more information about management capacity).

Table 1. Pros and Cons of Different Fishery Management Approaches

APPROACH	DESCRIPTION	PROS	CONS (OR CHALLENGES)
Total allowable catch (TAC)	Sets a limit on the amount of total harvest permitted	Can cap harvest at a sustainable level	May incentivise the race to fish, high-grading (discarding of low-valued fish) and misreporting; may be difficult to enforce, particularly in artisanal fisheries
Individual quota (IQ)	Assigns a property right to portions of a quota	Can cap harvest at a sustainable level; may promote economic efficiency (particularly if rights are tradeable); incentivises management for long-term sustainability	Privatisation of public resource; may be difficult to assign rights; consolidation of IQs by individuals or firms
Territorial use rights for fishing (TURFs)	Area-based management in which specific users have rights to access one or more fish resources	Incentivises management for long-term sustainability	Additional management measures may be needed to cap extraction at sustainable levels; determining the appropriate size of TURFs may be complicated
Community-based co-management	Local people are allowed to participate in decision-making and enforcement	May facilitate monitoring and enforcement	More likely to function well for high-valued stocks; too many stakeholders may hinder effective management
Permits	Restrict the number of users who are able to access the resource	May reduce fishing pressure; may improve enforcement	Additional management measures may be needed to control quantity of harvest
Gear restrictions	Rules regarding the number, types and designs of gear permitted in a fishery	May protect spawning females, juveniles, largest fish or protected species and assure that fish get to reproduce before being caught (e.g. mesh-size requirements); may protect habitats (e.g. ban on dynamite fishing); may minimise bycatch; useful for data-limited fisheries	Additional management measures may be needed to control quantity of harvest; can be difficult and costly to enforce; do not necessarily promote economic well-being

Table 1. Pros and Cons of Different Fishery Management Approaches (continued)

APPROACH	DESCRIPTION	PROS	CONS (OR CHALLENGES)
Size limits (commonly related to gear restrictions)	Designed to protect a particular stage, age or size of targeted species	May protect larger, potentially more productive fish, or young fish until they reach reproductive age	Additional management measures may be needed to control quantity of harvest; do not necessarily promote economic well-being; spawning size may increase or decrease
Seasonal closures (in all or at particular fishing sites)	Temporary closures, often set to protect sensitive portions of the life cycle	May protect juveniles, spawning fish or the whole stock; easy to implement	Additional management measures may be needed to control quantity of harvest; may cause excess capacity
Buybacks	Purchasing fishing gear, vessels, quota or permits to reduce excess capacity and/or improve profitability in the sector	May decrease incentives to overharvest; may reduce fishing pressure; may aid in protecting sensitive species	Potential for capacity to rebuild or gains in efficiency to counteract buyback program; competing fleet may increase
Ban discards	Aimed at eliminating or minimising fish caught and discarded at sea (i.e. all harvest must be landed)	May reduce fishing pressure per quantity landed; may incentivise direct or indirect consumption of less desirable fish; results in better extraction information, which may improve assessments	Additional management measures may be needed to control quantity of harvest; difficult to enforce; requirement to land choke species could prematurely close target fisheries
Harvest control rules designed to maintain stocks at productive levels	Performance is evaluated using reference points (RPs) that describe desirable states (target RPs) and threshold states to avoid (limit RPs)	Provide fishery managers with (ideally) scientifically and economically justified targets	Reference points can be hard to estimate and enforce in real time, and may also change over time
Ecosystem-based management	Management that recognises the dynamic nature of ecosystems, and human-nature interactions and effects of interactions throughout the system	Can address broader objectives than the more common focus on managing individual species in isolation	Interactions are complex and can be difficult to clearly identify; basic information is not always available; ecosystem may change to an alternative state
Marine protected areas (MPAs) and refugia	Areas in which extractive activities are limited or prohibited	May result in fishery benefits through larval export and spillover (i.e. movement of juveniles or adults from the MPA to the adjacent fishable area); may increase food provision where fisheries have been overfished; MPA effects will be strongest for Fully Protected MPAs, which prohibit extractive or destructive activities and minimise all impacts (also referred to as marine reserves) (OSU et al. 2019)	Benefits from larval export and spillover are often uncertain; may increase cost of fishing; may promote overfishing at the boundaries of the MPA; difficult to finance; may generate social conflicts; often not easy to set in the proper area due to conflicting interests
Regional management organisations	Organisations that coordinate management for fish stocks that exist in multiple political boundaries	May result in improved management for transboundary, straddling stocks or stocks that will shift spatially in the future	Domestic political issues may impede thorough regional enforcement of straddling stocks; international conflicts may arise

Sources: Anderson et al. (2019); Costello et al. (2016); Fulton et al. (2011); Gelcich et al. (2010); Cabral et al. (2019); Hilborn and Ovando (2014); Hilborn et al. (2004); Jentoft et al. (1998); Lester et al. (2016); Pons et al. (2017).

3. Mariculture

Aquaculture is the cultivation of aquatic animals and plants. In this section, we focus primarily on mariculture, which is aquaculture that occurs at sea and on coasts (e.g. coastal ponds and lagoons) (FAO 2018). Freshwater aquaculture is excluded in this report as it is outside the scope of food potential from the sea—however, it is important to recognise that freshwater/inland aquaculture currently represents the majority (64 percent) of current aquaculture production and may have important expansion potential (FAO 2018). However, land-based aquaculture competes with other sectors for freshwater and land for production sites—neither of which are as constraining for mariculture production (Gephart et al. 2014).[9]

In this section, we focus on two types of mariculture: (1) unfed mariculture (e.g. macroalgae and filter-feeders) and (2) fed mariculture (e.g. finfish, crustaceans and gastropods). Unfed mariculture produces organisms that extract food resources from the surrounding environment, while fed mariculture produces organisms that depend on direct feed inputs. First, we describe the current status and trends of aquaculture broadly, focusing on mariculture production. We then discuss the production potential for the two types of mariculture. Mariculture production is not limited by the same biological and ecological constraints as capture fisheries, and we find it has the potential to greatly expand.

3.1 Current Status and Trends

The aquaculture sector has and continues to experience production growth. Unlike the capture fishery sector, the aquaculture (i.e. freshwater and marine) sector continues to expand significantly. Between 2011 and 2016, annual growth in total aquaculture production (excluding aquatic plants) was 5.8 percent, reaching an estimated 80 mmt in total production (FAO 2018).

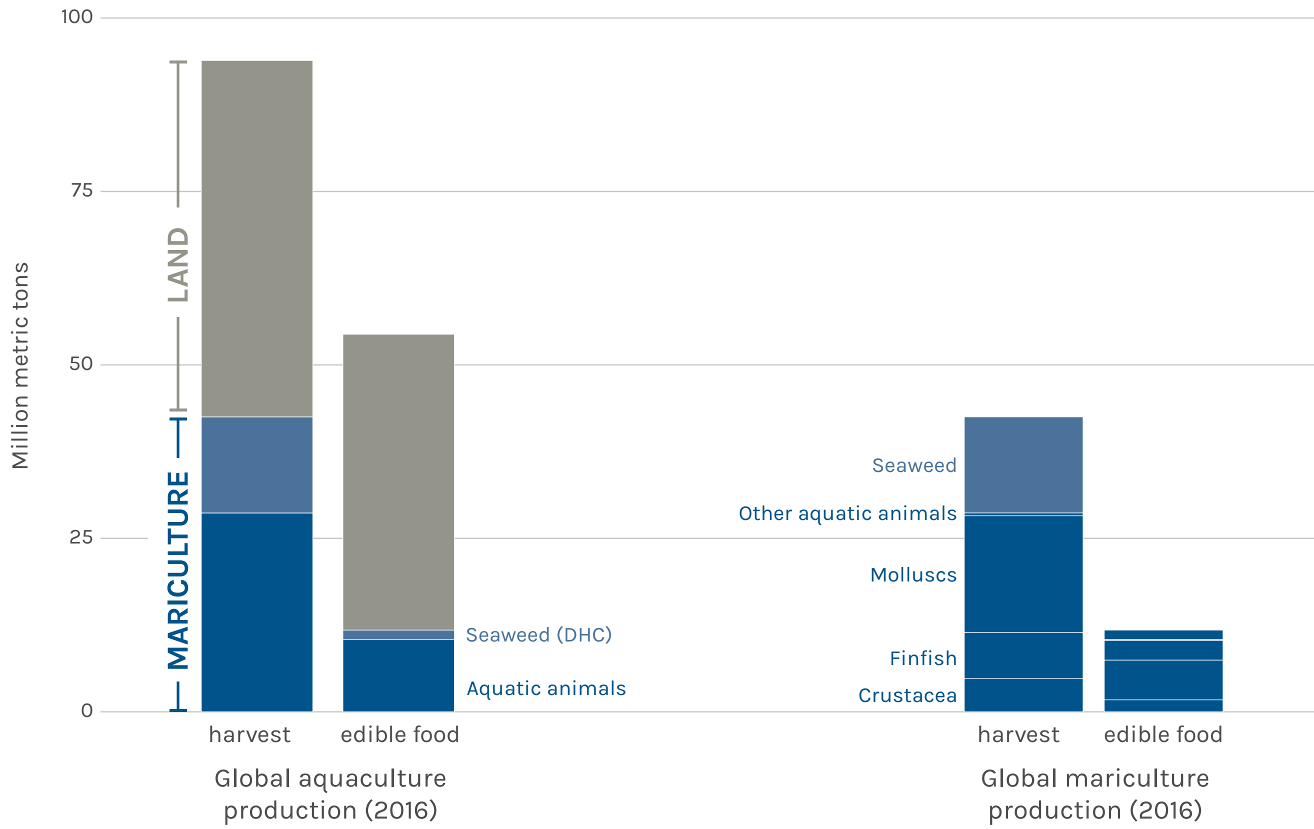
In terms of marine animals, mariculture produced 29 mmt in 2016, which represents over one-third of fish aquaculture production and about a quarter of all marine fish production (FAO 2018) (Figure 3).[10] Over half of mariculture production of marine animals is shelled molluscs, while finfish and crustaceans represented 23 percent and 17 percent, respectively (FAO 2018). When these volumes are converted to edible food equivalents, finfish mariculture provides more food by volume than shelled molluscs (Edwards et al. 2019).

The vast majority (97 percent or 30 mmt) of aquatic plant production is farmed, and about half of cultivated seaweed is used as human food. China and Indonesia account for more than 85 percent of this production (FAO 2018). Certain seaweed species, including *Undaria pinnatifida*, *Porphyra spp.* and *Caulerpa spp.*, are produced specifically for direct human consumption, but most of the recent growth has been driven by the rapid farming growth in Indonesia for two seaweed species (*Kappaphycus alvarezii* and *Eucheuma spp*.,) that are used in the production of food additives and for other purposes (FAO 2018). About 46 percent of all seaweed production (or 14 mmt) was used for human food in 2016; the remainder was consumed indirectly through processed foods and used in other industries that produce, for example, fertilizers, medical products and animal feed ingredients (Buschmann et al. 2017; Loureiro et al. 2015). Most seaweed destined for human consumption is dried—when converted using the dry weight:fresh weight ratio of 0.1, 14 mmt is equivalent to 1.4 mmt of edible food (Duarte et al. 2017). While seaweed's production and direct consumption are relatively new in Western countries, many Asian countries, where seaweeds are consumed frequently, have well-established mariculture operations (SAPEA 2017).

9. Mariculture (particularly fed) may indirectly compete with these sectors due to its reliance on agricultural products for feed ingredients (e.g. soy), water for processing and resources for hatcheries.

10. This description does not include seaweed production, which is discussed later in this section.

Figure 3. Aquaculture (Left) and Mariculture (Right) Production in 2016 of Aquatic Animals and Seaweed Destined for Direct Human Consumption



Note: DHC = direct human consumption. The asterisk represents seaweed (DHC). Harvest values are converted into edible food using conversion values from Edwards et al. (2019) and Duarte et al. (2017).

Source: FAO (2018).

Additionally, 89,000 metric tons of microalgae (i.e. *Spirulina spp.*) are farmed and used in human nutrition supplements since they are rich in protein, vitamins, lipids and probiotic properties (FAO 2018; Khan et al. 2018). Although there is growing interest in ocean microalgae cultivation systems, the majority of current production occurs on land and is therefore outside of the scope of this report (Park et al. 2018).

Major differences exist in the current status and potential for expansion of *fed* versus *unfed* mariculture. While many species are grown in mariculture, it is imperative to distinguish those that are fed from those that are unfed. Fed mariculture, such as finfish and crustaceans, requires feed inputs to supply the farmed animal with the essential protein, fats and nutrients to grow. Unfed species, such as bivalves and seaweed, do not require human-derived feed inputs and instead extract resources from the surrounding environment (e.g. phytoplankton). While the production of both fed and unfed species has increased, total growth for fed species has been greater (FAO 2018), in part due to increasing demand for such species (e.g. salmon). In response to growth in fed aquaculture, feed production for fed species increased 600 percent (from 8 to 48 mmt) over a 20-year period (Tacon et al. 2011; Hasan 2017). Future production potential for fed mariculture species is tightly coupled to feed availability and access, while unfed mariculture production is constrained by the limitations of the ecological carrying capacity of local environments, particularly under climate change.

3.2 Unfed Mariculture Production Potential

Unfed mariculture is the production of organisms that do not require direct feed inputs for cultivation and include primary producers such as seaweeds and herbivores or filter-feeders (e.g. bivalves) (SAPEA 2017). These species are ecologically efficient as they are low on the food chain (SAPEA 2017). In addition, production of unfed species does not depend on feed inputs and is often less reliant on chemical inputs than production of fed species, which means the former can have a reduced impact on the environment, and even improve it (Theuerkauf et al. 2019; Alleway et al. 2018; Gentry et al. 2019; van der Schatte Olivier et al. 2018). Unfed mariculture operations are comparatively less resource-intensive than fed mariculture, which relies on land and freshwater for the production of terrestrial-based feed ingredients.

Aquatic plants

Seaweed is the fastest growing aquaculture sector, and there is potential for a significant increase in food production from macroalgae. There is increasing interest in using seaweed mariculture to help solve food security issues, replace fossil fuels with seaweed bioethanol and biomethane, act as a form of carbon sequestration and reduce ruminant methane emissions, to name a few potential benefits (Chung et al. 2011; N'Yeurt et al. 2012; Sondak et al. 2017; Duarte et al. 2017; Capron et al. 2018; Froehlich et al. 2019; Brooke et al. 2018; Roque et al. 2019; Machado et al. 2016), but achieving any of these goals would necessitate a massive increase in seaweed production. For example, using the same assumptions outlined in Forster and Radulovich (2015), replacing just 1 percent of humans' diet with seaweed would require increasing global production by 73 times total current production, or 147 times current seaweed production for human food.

How could the world achieve meaningful expansion of seaweed supply? A new study finds that 48 million km^2 of the world's ocean is suitable (based on nutrient availability and temperature) for seaweed cultivation. These waters span 132 countries, of which only 37 are currently cultivating (Froehlich et al. 2019). There are many different methods for increasing macroalgae biomass production in the ocean, including adopting new harvest styles, farming in areas with elevated nutrient loads, breeding species with enhanced genetics and using new farming technologies (Capron et al. 2018; "Oilgae Guide to Fuels from Macro Algae | Algae Fuel | Seaweed" n.d.; Czyrnek-Delêtre et al. 2017; Benzie et al. 2012; Loureiro et al. 2015). More research is needed to determine the production potential of seaweed as a cost-effective and competitive food source, as well as how much it could reasonably contribute to food security given preferences and economic considerations (e.g. the existence of markets for different uses).

Seaweed is being explored as an alternative feed ingredient. Seaweed contains long chain omega-3 fatty acids, which are essential in some feed formulations and typically supplied by fish oil. Currently, only about 1 percent of all seaweed production is estimated to be currently used as feed across all systems (FAO 2019). Replacing fish oil with seaweed oil may reduce mariculture's dependence on capture fishery production for future expansion (Bjerregaard et al. 2016). In addition, recent research suggests that feeds using some species of seaweeds may result in reduced methane production from ruminants, which could reduce greenhouse gas emissions from other animal production sectors (Maia et al. 2016; Brooke et al. 2018; Roque et al. 2019; Machado et al. 2016). However, the nutritional content varies among seaweed species, and thus some species will not have the EPA and DHA (types of omega-3 fatty acids) content required to serve as adequate replacements for fish oil (Rajauria 2015). Existing research demonstrates that some seaweeds have the potential to contribute meaningfully as a cost-effective feed ingredient for livestock and some mariculture, but variations in chemical composition across species make their widespread use in animal feed challenging (Rajauria 2015). More research is needed to determine the potential for different seaweeds to be used as ingredients for animal feed.

Currently, there are economic, technological and regulatory barriers to widespread seaweed production expansion. Before macroalgae mariculture can be used to address food security, biofuel production and carbon sequestration goals globally, the economic and technological obstacles impeding expansion and intensification of seaweed farming will need to be addressed, particularly in the Western world ("Oilgae Guide to Fuels from Macro Algae | Algae Fuel | Seaweed" n.d.; Roesijadi et al. 2010; Aitken et al. 2014; Pechsiri et al. 2016; Seghetta et al. 2016; Jiang et al. 2016; Fernand et al. 2017). Among the technological constraints are a lack of both offshore production techniques and cost-effective and efficient harvesting systems (SAPEA 2017; Froehlich et al. 2019). Assuming that technological innovations allow new areas of the ocean to be farmed for food production, make biofuel production energy efficient enough to be employed and enable seaweed carbon sequestration to become feasible, these three end-uses will still need to become cost competitive with other seaweed market goods and competing sources of food, fuel and carbon abatement[11].

Regardless of whether seaweed mariculture continues to expand globally, a number of environmental concerns require further research. A recent study of the environmental risks associated with intensifying seaweed mariculture in Europe found multiple potential drivers of environmental change, including light shading; absorption of nutrients; reduction of kinetic wave energy; increase in noise; release of artificial materials; new habitat for diseases, parasites and other organisms; introduction of non-native species; release of reproductive materials; and release of dissolved and particulate matter (Campbell et al. 2019). While some of these environmental drivers have the potential to bring positive change—such as reduction of wave height during storms, provision of additional habitat for at-risk species and improvement of water quality in eutrophic, hypoxic and/or acid locations—many need to be more closely researched to ensure that seaweed farms minimise negative impacts on species and ecosystems (Froehlich et al. 2019; Campbell et al. 2019). Indeed, no production system can have zero impact, and the benefits gleaned from unfed mariculture production do not mean that it should not be subject to regulation, standards or oversight.

Monitoring of seaweed farms will be important to ensure that they do not become vectors for diseases, parasites and invasive species, and to determine the amount of infrastructure lost due to wear and tear or accidents (Campbell et al. 2019). As with other mariculture systems, understanding how farms could affect larger marine mammals and how different farm structures could increase or decrease the risk of marine mammal entanglement will also be important (Campbell et al. 2019). Additional life cycle assessments will be needed to understand the global warming potential of cultivating seaweed for different end-uses, as well as other environmental impacts—such as ecosystem and human toxicity (Roesijadi et al. 2010; Fernand et al. 2017). Seaweed mariculture production sites are being studied in locations around the world, including Norway and the United States, and continued research will improve the understanding of potential environmental risks and benefits (Froehlich et al. 2017a).

Compared with major agricultural products in the United States, there is some evidence that seaweed production is expensive (Forster and Radulovich 2015), partly because most farmed seaweed must be dried after harvest. However, there is a substantial opportunity to reduce production costs through larger-scale development, mechanisation, and improved breeding and selection for important traits (e.g. growth and composition) (Forster and Radulovich 2015). In addition, because some seaweed species are fast-growing and can be grown year-round, yield per unit area can surpass that of terrestrial crops: in China, annual yield per hectare for *L. japonica* is 20 mt, compared to 10 mt and 3 mt for corn and soybeans in the United States, respectively (Forster and Radulovich 2015). Land-based systems have greater access to investments, subsidies and insurance—increased access to these resources could help promote innovations and advancements needed to increase efficiency and reduce costs.

11. Neither seaweed biomethane nor bioethanol are currently economically practical at a global scale. If we assume it is possible to sequester all the carbon contained within seaweed biomass with no additional costs, then the carbon abatement price, or dollars per ton of carbon dioxide avoided, using seaweed is $763/mt CO_2. This price is several times higher than other more common forms of carbon abatement, which typically range from $25 to $105/mt CO_2 offset (Gillingham and Stock 2018). Economically, seaweed bioethanol would be $10.73/gal, which is more than twice the global average of $4.35/gal of gasoline (Forster and Radulovich 2015; GlobalPetrolPrices.com 2019). In addition, life cycle environmental impact assessments of seaweed bioethanol production have found the process to be very energy- and carbon-inefficient.

Similarly to other types of mariculture, there are regulatory barriers to the widespread production of seaweed as a food source in some locations. The United States has no established policy for the sale of seaweed destined for direct human consumption (DHC) in large quantities and across state lines in unprocessed forms, making it difficult for producers to market.

Filter-feeders

Filter-feeders obtain their nutrition from organic matter suspended in their surrounding environment. Marine bivalves (e.g. mussels, clams and scallops) are filter-feeders cultivated in mariculture operations, which, like seaweed, do not rely on feed inputs. For this reason, potential production is much higher than current production. Gentry et al. (2017) find that over 1.5 million km^2 (roughly the size of Mexico) of marine habitat, spanning temperate and tropical regions, are suitable for bivalve production and that developing small suitable areas can result in high production volume (e.g. they find that developing just 1 percent of Indonesia's suitable area could produce over 3.9 billion individual bivalves).

A follow-up study (Costello et al. n.d.) builds on Gentry et al. (2017) to estimate production potential when including economic considerations (i.e. production costs and profitability). This study finds that the ocean has the potential to produce nearly 768 mmt[12] of bivalves, and about 60 percent of this production would be profitable at roughly the current price for blue mussels (1,700/mt). However, mariculture currently produces just 15.3 mmt of bivalves per year. If the potential is so large, why is our production so low? This large gap is likely driven in part by prohibitive regulatory barriers in many countries (Wardle and Morris 2017; Sea Grant 2019). For example, despite having one of the largest exclusive economic zones and longest coastlines, the United States has missing or restrictive mariculture regulations and only produces 1 percent of global bivalve mariculture. Regulations related to bivalve mariculture are often driven by food safety concerns—bivalves and seaweeds must be cultured in clean water because they can absorb pollution, toxins and bacteria in the water, which can then be passed on to consumers. Offshore waters, which are typically cleaner, offer an opportunity for expansion but can entail higher cultivation costs than their nearshore counterparts (Froehlich et al. 2017a; Holmer 2010).

3.3 Fed Mariculture Production Potential

Unlike that of seaweeds and bivalves, the production potential of fed mariculture (e.g. finfish and crustaceans) is currently challenged by feed availability in addition to economic viability and regulations. When considering environmental suitability, Gentry et al. (2017) found considerable global production potential for finfish mariculture in both temperate and tropical regions. They estimated that the biological potential for finfish mariculture production is 15 billion metric tons (bmt) of finfish annually, over 100 times what is produced by wild fisheries. They also found that the most productive regions, representing 0.015 percent of the ocean's surface area (for comparison, an area smaller than Lake Michigan), could provide as much as the total current harvest from global capture fisheries (Gentry et al. 2017). This estimate assumes that production is not limited by current feed availability.

Costello et al. (n.d.) build on Gentry et al. (2017) to estimate production potential considering economic factors (i.e. costs and profitability) and future feed scenarios in addition to environmental suitability. This study finds that production potential may be challenged by feed availability—assuming current feed practices, dependencies on FM/FO and availability of whole fish and by-products available for indirect human consumption (IHC), finfish production, which currently involves mainly carnivorous fish species, is limited to 14.4 mmt. However, it has the potential (in a scenario unconstrained by feed made from fish products) to produce 1,000 times more annually. The comparatively high cost of finfish mariculture also challenges production—we find that under current feed availability and feed conversion rates, finfish production only becomes economically viable when price equals $5,000/mt, which is nearly four times the current average seafood price in capture fisheries but lower than the current price for Atlantic salmon ($7,000/mt).

12. All volumes reported as shell-on or live weight unless otherwise noted. When converted, 768 mmt is equal to 131 mmt of edible food.

A large proportion of mariculture feeds is typically derived from land-based ingredients and fishmeal and fish oil (FM/FO), which is derived from fish products. FM/FO is produced using whole fish from targeted (mainly forage fisheries) and non-targeted fisheries (includes multiple species of low-value food-grade fish and fish unfit for human consumption), as well as fish processing wastes (i.e. trimmings) (Cao et al. 2015). The fraction of capture fishery harvest destined for reduction into FM has declined recently, possibly due to overfishing and El Niño effects (FAO 2018). The development of fed mariculture could be impacted by unstable supply and increasing unit cost of FM/FO.

Fortunately, the aquaculture industry has begun to make tremendous strides in finding alternatives to marine ingredients and developing feeds that provide adequate nutrition for the growth of fish and crustaceans (Little et al. 2016; Gasco et al. 2018). The replacement of FM/FO with non-fish ingredients, such as land-based proteins, plant and animal by-products, and microbial products, has reduced the reliance of aquaculture feed on fish from capture fisheries (Tacon et al. 2011; Hasan and New 2010; Little et al. 2016; Porritt and McCarthy 2015; Waite et al. 2014). 'Fish in, fish out' (FIFO) ratios, which describe the amount of capture fishery landings required to produce a unit of farmed fish, are expected to continue to decline as alternative sources of protein continue to be developed. For example, fishmeal and fish oil inclusion rates in Atlantic salmon diets have dropped by 41 percent and 8 percent respectively, and some salmon can now be bred to be completely vegetarian (Aas et al. 2019). However, fishmeal and fish oil inclusion rates are still very high for some fish species (e.g. eels), although they represent proportionally a smaller amount of total aquaculture production (Froehlich et al. 2018c). While this movement away from targeting wild capture fish as inputs to aquaculture feed is promising in that it would generate more wild food from the sea, there are important technological, nutritional and economic constraints to FM/FO substitution and many substitutes being explored are currently too expensive to incorporate in large-scale production (Naylor et al. 2009). See Section 3.4 for a more detailed discussion of the pros and cons of different feed alternatives.

3.4 Threats to Unfed and Fed Mariculture Production

Habitat degradation and pollution

Marine pollution threatens the sustainable development of mariculture, just as it threatens wild fisheries. Because both capture and mariculture fisheries are affected by habitat degradation and pollution, we discuss the implications together in Section 7.6.

Disease and parasites

Like farming on land, mariculture production is vulnerable to disease and pest outbreaks. Diseases can move between farmed and capture fisheries, threatening the productivity of both operations (Clavelle et al. 2019). Disease and parasite transmission remain major challenges for mariculture expansion, and sustainable approaches for addressing this issue are typically expensive compared to the more common practice of using prophylactic applications of antibiotics and fungicides (Klinger and Naylor 2012). This practice can result in resistant strains of diseases and parasites, which can have major implications for both farmed and wild fish stocks, and can move to humans via consumption. These outbreaks can result in significant economic consequences for mariculture producers (Lafferty et al. 2015). Recommendations for reducing disease and parasites include lowering densities, avoiding prophylactic treatment, using narrow spectrum antibacterials and quality feed inputs, managing the surrounding environment (e.g. soil and water quality) and spacing mariculture operations to minimise connectivity to other mariculture or wild stocks (Primavera 2006; Klinger and Naylor 2012). Selective breeding and genetic modification are also being used to develop, among other traits, disease resistance in commercially important aquaculture species (Klinger and Naylor 2012).

Table 2. List of Current Most Popular Alternative Ingredients to Replace FM/FO

CATEGORY	PROS	CONS	SOLUTIONS AND OPPORTUNITIES
Terrestrial plant-based ingredients, including crop by-products (e.g. rapeseed, wheat flour, soybean meal)	Easily accessible and can be produced in large quantities; economically competitive	Presence of anti-nutritional factors; low digestibility; poor palatability; imbalanced amino acid profile; do not contain nutritional benefits of omega-3 fatty acids	Apply more advanced processing technology or enzymatic treatment to enhance nutritional quality; add attractants or palatants; can be modified via advanced genetics techniques to have long-chain fatty acids
Terrestrial animal by-products (e.g. poultry meal, feather meal, blood meal)	Readily available; economically competitive; free from anti-nutritional compounds	Nutritional quality largely depends on processing technology; high in saturated fats and less healthy fatty acids; must be blended with polyunsaturated fats; use limited by regulations related to perceived disease risk; do not contain nutritional benefits of omega-3 fatty acids	More advanced processing technology; supplementation of essential amino acids; increase awareness and improve consumer perception
Seafood and aquaculture processing waste (e.g. fish head or bones)	Potential availability is substantial due to the large amount of processing waste (30–70% of fish volume)	Nutritional limitations; need for infrastructure; costly to transport; risk of contaminants	More advanced processing technology
Microbial ingredients (e.g. bacteria, microalgae and yeast)	Compatible nutritional profile; some (but not all) have significantly lower greenhouse gas emission intensities than land-based alternatives	Limited nutrient bioavailability due to rigid cell walls; high production cost	More advanced processing technology; scale to bring down the cost
Under- and unexploited fishery resources (e.g. zooplankton, krill and mesopelagic species)	Large biomass potential; not used for direct human consumption	Exploitation could have significant ecosystem impacts; difficult to assess stock size and dynamics; technological innovations needed for increased exploitation and exploration	Improve stock assessments to increase understanding of stock composition and exploitation potential; recommend precautionary approach
Genetically modified (GM) plant ingredients	Disease/pest resistance; higher nutritional quality; longer shelf life; free from anti-nutritional factors; cost competitive	Regulatory limitation; mixed positive and negative effects on nutrient balance and growth; negative consumer or producer attitudes	Get adopted by legislation; enhance consumer awareness; further study to understand anti-nutritional aspects of GM ingredients and possible expression of transgenic DNA in fish
Insects (e.g. black soldier flies, silkworm, termites)	Rich protein content; favourable lipid profiles; readily produced	Presence of indigestible chitin in exoskeleton; bioaccumulation of pesticides; low amount of polyunsaturated fatty acids in terrestrial insects; need to scale	Technological improvements to enhance mass production; improve understanding of the effect of insect meal on fish health; increase awareness and improve consumer perception

Sources: Bandara (2018); Gasco et al. (2018); Kim et al. (2019); Little et al. (2016); Popoff et al. (2017); Ssepuuya et al. (2019); Hoegh-Guldberg et al. (2019); Tacon et al. (2011); Osmond and Colombo (2019).

Climate change

Similar to its effect on capture fisheries, climate change is expected to have mixed effects on the production potential in mariculture operations. A recent study that examined the potential impacts of climate change (e.g. changes in sea surface temperature, primary productivity and ocean acidification) on finfish and bivalve mariculture production finds that while the global production potential for both sectors declines with climate change, increases are observed generally in polar and subpolar regions, as well as some tropical and subtropical regions (e.g. areas in the Caribbean and Mediterranean Seas), mostly for finfish (Froehlich et al. 2018a). In contrast, nearly every country that currently has suitable waters for bivalve production is expected to experience a decrease in production potential by the end of the century, driven by a combination of changing temperature, shifts in primary production and ocean acidification (Froehlich et al. 2018a). Other effects of climate change that could negatively impact mariculture production include the increased threat of invasive species interactions with shifting spatial ranges (Barange et al. 2018; Clavelle et al. 2019), negative impacts on the physiology of fish (Cochrane et al. 2009), extreme weather events, sea level rise, unstable FM/FO supplies and increased incidence of harmful algal blooms (HABs) and disease events (Solomon et al. 2007) (see Section 7.5 for more information about HABs).

Feed challenges

For fed species, feed constraints could challenge mariculture expansion. While the aquaculture industry has significantly improved feed efficiency, the total amount of FM/FO used for aquaculture feed has increased with the rise in volume of aquaculture production (Klinger and Naylor 2012). The expansion of the aquaculture sector has not increased the extraction for capture fisheries destined for IHC—rather, FM/FO use has shifted from other farmed animal groups (e.g. pigs and poultry) to aquaculture production (Froehlich et al. 2018c). The continued expansion of fed mariculture will require FM/FO replacements (Table 2), which must be nutritionally suitable, readily available, priced competitively and easy to transport (Klinger and Naylor 2012; Cao et al. 2015; Little et al. 2016). The potential for and challenges of exploring alternative feed proteins are highlighted in Table 2 (Klinger and Naylor 2012; Cao et al. 2015; Little et al. 2016; Popoff et al. 2017; Bandara 2018; Gasco et al. 2018; Kim et al. 2019; Ssepuuya et al. 2019). Fish oil will be more difficult to replace than fishmeal as it contains long-chain omega-3 fatty acids, which are important for fish health and offer health benefits for consumers (Klinger and Naylor 2012). This nutritional aspect may be compromised as FM/FO is replaced with terrestrial crop products, and the nutritional quality of feed may have important implications for the nutritional content of the end product. If production costs are lowered, microalgae may be a viable substitute for fish oil since they are high in omega-3 fatty acids (Benemann 1992; Shah et al. 2018). While cost has been a barrier to the widespread production and use of many feed alternatives, there has been progress: algae oil and insect meals are currently on the market (e.g. AlgaPrime™ DHA). They are more expensive than forage fish but produced at a high enough scale for use in salmon feeds.

Several conventional (such as terrestrial plant-based proteins and animal by-products), non-conventional and innovative ingredients (such as single-cell organisms, insects and microalgae) are being explored as potential feed inputs for aquaculture (Cottrell et al. n.d.). Plants can also be genetically engineered to produce long-chain omega-3 fatty acids, reducing FO feed requirements. There is an increasing trend to use by-products from fish processing to replace fishmeal. Even aquaculture itself is becoming a major source of fishmeal and fish oil through the reuse of processing waste. However, there are barriers to the widespread adoption of these substitutes, including high costs, data limitations, variable production, high perishability and potentially large ecosystem impacts (e.g. in the case of krill and mesopelagic fisheries) (Klinger and Naylor 2012; Cao et al. 2015; Little et al. 2016; Popoff et al. 2017; Bandara 2018; Gasco et al. 2018; Kim et al. 2019; Ssepuuya et al. 2019). Current technological advances such as advanced processing technology, synthetic biology, selective breeding and genetic modification offer many ways to overcome those barriers and achieve further gains in feed conversion efficiency (Kim et al. 2019).

While the science and technology to advance the use of alternative feeds is increasingly available, other hurdles for broader adoption of alternative feeds include lack of consumer awareness and farmer demand. To help drive demand and consumer acceptability, engaging with the sustainable seafood movement (certifications, advisory lists and market-based initiatives) to highlight feed sustainability may be important.

Political and regulatory constraints

Unclear or heterogeneous regulations and policies in Westernised nations may be one of the greatest barriers to the expansion of mariculture. For example, a permitting process that takes 10 years may pose a significant barrier to initiating production. Many regulations are intended to prevent environmental degradation and protect consumers from contaminated products. Currently, the full implications of large-scale mariculture are unknown, and thus many governments outside of Southeast Asia have precautionary regulations. Still, our understanding of the potential environmental and social implications has improved over the last two decades, and lessons from effective fisheries management and land-use regulations could help guide sustainable mariculture expansion. For example, standards regarding water quality, zoning, ecosystem damage, pollution, pathogen transmission and fish escapes, as well as a system for monitoring relevant metrics, could be used (Klinger and Naylor 2012). Policymakers could provide incentives or support for the creation of cost-effective feed substitutes and scalable ecosystem-based mariculture systems, as well as disincentives for pollution, habitat destruction and other forms of environmental degradation through strong oversight operations and standardised reporting, for instance. Market-based approaches could be developed to incentivise environmentally sustainable expansion practices.

3.5 Mariculture Expansion Approaches

Compared to capture fisheries and other major food systems, the emerging sector of mariculture appears to be globally underdeveloped. The reasons for this include regulatory barriers, prohibitive costs, social aversion and associated uncertainties. At the same time, in some locales, unwise or unregulated expansion has led to pollution, destruction of critical marine habitats and conflicts with other sectors and resource users. To expand mariculture so that it can contribute meaningfully to global food security, care must be taken to limit environmental harm and social conflicts. In Table 3, we outline potential pathways forward, largely based on Klinger and Naylor (2012).

Table 3. Pros and Cons of Different Mariculture Pathways and Approaches

PATHWAY OR APPROACH	DESCRIPTION	PROS	CONS
Environmental standards and regulations	Standards (e.g. water quality) set and monitored by governing agency	May help reduce incidents of disease transfer, nutrient and chemical pollution and habitat loss	Expensive; prohibitive if unstructured or poorly defined
Seafood traceability	Tracing a seafood product through the entire supply chain	Enhances food safety; improves operational efficiency and market access; helps eliminate illegal activities; helps mitigate fraud and counterfeiting	Expensive; proprietary information conflicts; involves federal and state or provincial policies
Marine spatial planning	Coordinated spatial planning that considers scientific and economic information and other resource users; could build on land-use policy and market-based approaches on land	Prioritises mariculture placement based on the available information; may help reduce conflict with other user groups; can be used to place farms in ways that minimise disease transfer and interactions with wild species	Expensive; may be time-consuming; needs to adapt as environmental conditions and social preferences change
Sustainable sourcing for alternative feeds	FM/FO replaced by terrestrial crops, rendered terrestrial animal products, fish processing waste and other novel products	Reduces fed mariculture's dependence on capture fisheries for expansion	Current barriers to widespread adoption (e.g. high costs); may affect the health of fed species and/or health benefits for consumers

Table 3. Pros and Cons of Different Mariculture Pathways and Approaches (continued)

PATHWAY OR APPROACH	DESCRIPTION	PROS	CONS
Selective breeding	Breeding organisms with desirable traits in order to produce offspring with improved traits	May improve feed efficiency; may improve disease resistance, reducing antibiotic use (which reduces risk of antibiotic-resistant disease strains)	Escaped mariculture species may interact with wild populations, which can lead to hybrids with reduced fitness
Genetic modification	Gene transfer to improve certain traits	May improve feed efficiency; may improve disease resistance, reducing antibiotic use (which reduces risk of antibiotic resistant disease strains)	Escaped mariculture species may interact with wild populations, leading to hybrids with reduced fitness
Unfed mariculture	Farming lower-trophic-level species such as bivalves and aquatic plants	Improves water quality in the surrounding environment through filtering; does not require direct feed	Insufficient demand for low-trophic level production may preclude large expansion; dense cultivation of plants can block flows, creating environmental challenges; low edible conversion requiring more production per pound; more sensitive to climate change; diverts nutrients from surrounding environment
Integrated multi-trophic mariculture	Farming of different trophic levels to reduce nutrient concentrations	In some cases, reduces nutrient and chemical pollution	Can be technologically challenging to implement; expensive
Offshore mariculture	Mariculture located in conditions similar to those of the open ocean	Less constrained by water or land availability for farming sites; may decrease nutrient and chemical pollution given the appropriate design and location (e.g. distance, depth and current); improves growth and condition (lower parasites and disease) of species; increases production without additional impact	Higher production costs; potential for interactions with wild fisheries; efforts to protect farmed animals can result in the harming or killing of large predators (e.g. sharks, seals)
Intensification	Concentrated and monoculture production systems	Can result in high yield per unit area	Increased risks of pollution, disease outbreak and the introduction of invasive species; may be less resilient; should be designed based on carrying capacity and should adopt ecosystem-based management
Selectivity in feeding	Feeding FM/FO at particular times in the life cycle and feeding in ways that do not put excess feed into the environment	Helps reduce nutrient pollution; may help reduce dependency on FM/FO	Can be expensive (e.g. requires technology to automate in offshore systems)
Selectivity in disease treatment	Using antibiotics only when necessary; development of vaccines	Reduces risk of antibiotic-resistant disease strains	Expensive compared to alternative approaches associated with environmental risks
Certification/ labelling/ ranking	Use market-based incentives to award and promote sustainable practices	Can incentivise greater adoption of sustainable mariculture systems and improve public awareness of sustainably farmed seafood	Certification process can be expensive and thus pose challenges for small operations; labelling can be confusing for consumers

Sources: Klinger and Naylor 2012; Clavelle et al. (2019); Froehlich et al. (2017a, 2018b, 2018c); Hall et al. (2011); Holmer (2010); Little et al. (2016); Shah et al. (2018); Ssepuuya et al. (2019); Wardle and Morris (2017).

4. Supply Curve of Food from the Sea

While the biological production potential for capture fisheries and mariculture is useful as an upper bound, actual production will depend on other factors, including production costs, demand for products, interactions with other sectors, and regulations. Here, we derive and analyse a 'sustainable supply curve' of food from the sea (Costello et al. n.d.). This supply curve provides an estimate of the sustainable quantity of seafood that could be produced at any given price. Our supply curve includes existing capture fisheries, unfed bivalve mariculture and fed finfish mariculture, and it assumes perfect substitutability across species. Seaweed[13] is excluded from the supply curve due to a lack of data. Because the capture fisheries and fed mariculture sectors interact via FM/FO, we present six scenarios representing varying assumptions about feed constraints driven by FM/FO availability and requirements. We report these projections in terms of edible meat as opposed to live-weight equivalents.

- **Scenario 1: FM/FO is produced from only the by-products of capture fisheries.** Eight percent of capture landings, in the form of trimmings or by-products, are utilised in FM/FO production.
- **Scenario 2: FM/FO is produced from both the by-products of capture fisheries and whole fish from directed reduction fisheries.** Eighteen percent of capture landings are caught specifically for FM/FO production, and 8 percent of the remaining landings are processed as by-products and directed to FM/FO production (24.6 percent of landings to FM/FO).
- **Scenarios 3a–c: FM/FO is produced from both by-products and whole fish as in Scenario 2, but the FM/FO demand of feed is reduced by 50 percent, 75 percent or 95 percent (3 sub-scenarios).** This reflects the potential for fish ingredients to be partially replaced by alternate ingredients in the near future. As in Scenario 2, 24.6 percent of capture landings are directed to FM/FO production.
- **Scenario 4: Finfish mariculture production is unconstrained by the availability of fishmeal and fish oil from capture fisheries.** This reflects the potential for fish ingredients to be entirely replaced by alternate ingredients. In this scenario, all capture landings are available for human consumption.

These scenarios were analysed in a data-driven global model of the sustainable supply of food from the sea. In that model, over 4,500 capture fisheries are modelled individually and aggregated to estimate the potential supply of wild fish at any given price, accounting for the costs of fishing and improved management. We used the Gentry et al. (2017) estimates of global mariculture potential as the biological potential for ocean finfish and bivalve mariculture. Gentry et al. (2017) excluded areas allocated for other uses (i.e. marine protected areas, oil rigs, major shipping areas) as well as areas more than 200 m deep (i.e. too expensive for development), thereby fully accounting for ocean zoning conflicts and partially accounting for financial feasibility. We then estimated the cost of finfish and bivalve production as the sum of the amortised capital costs and annual operating costs and only considered profitable areas as being viable for ocean mariculture. With this information we generated supply curves for bivalve and finfish mariculture production.

13. Studies suggest that seaweed could play an increasing role in diets—however, the majority of recent growth in production has been for carrageenan production rather than food production (FAO 2018), and the ability to significantly contribute to future diets given preferences is unclear.

At any given price, we calculate the sustainable supply as follows. For wild capture fisheries, we determine whether that price would economically justify the cost of improved fishery management. If it does, then the fishery is assumed to adopt improved management, which we operationalise as fishing at FMSY. If the price is insufficient to justify improved management, then we assume that the status quo fishing mortality continues. If neither management option is profitable, the fishery is not exploited and harvest equals zero. For mariculture, we examine each 0.21 degree patch of ocean to determine whether the patch is environmentally suitable and economically profitable for sustainable bivalve or finfish aquaculture. The patch is cultivated for the most profitable mariculture type or left uncultivated if neither venture is profitable. This procedure gives rise to a sustainable supply curve for capture fisheries and a sustainable supply curve for mariculture. To the extent that these products are substitutes, we can horizontally aggregate those supply curves to give an aggregate sustainable supply curve of food from the sea.

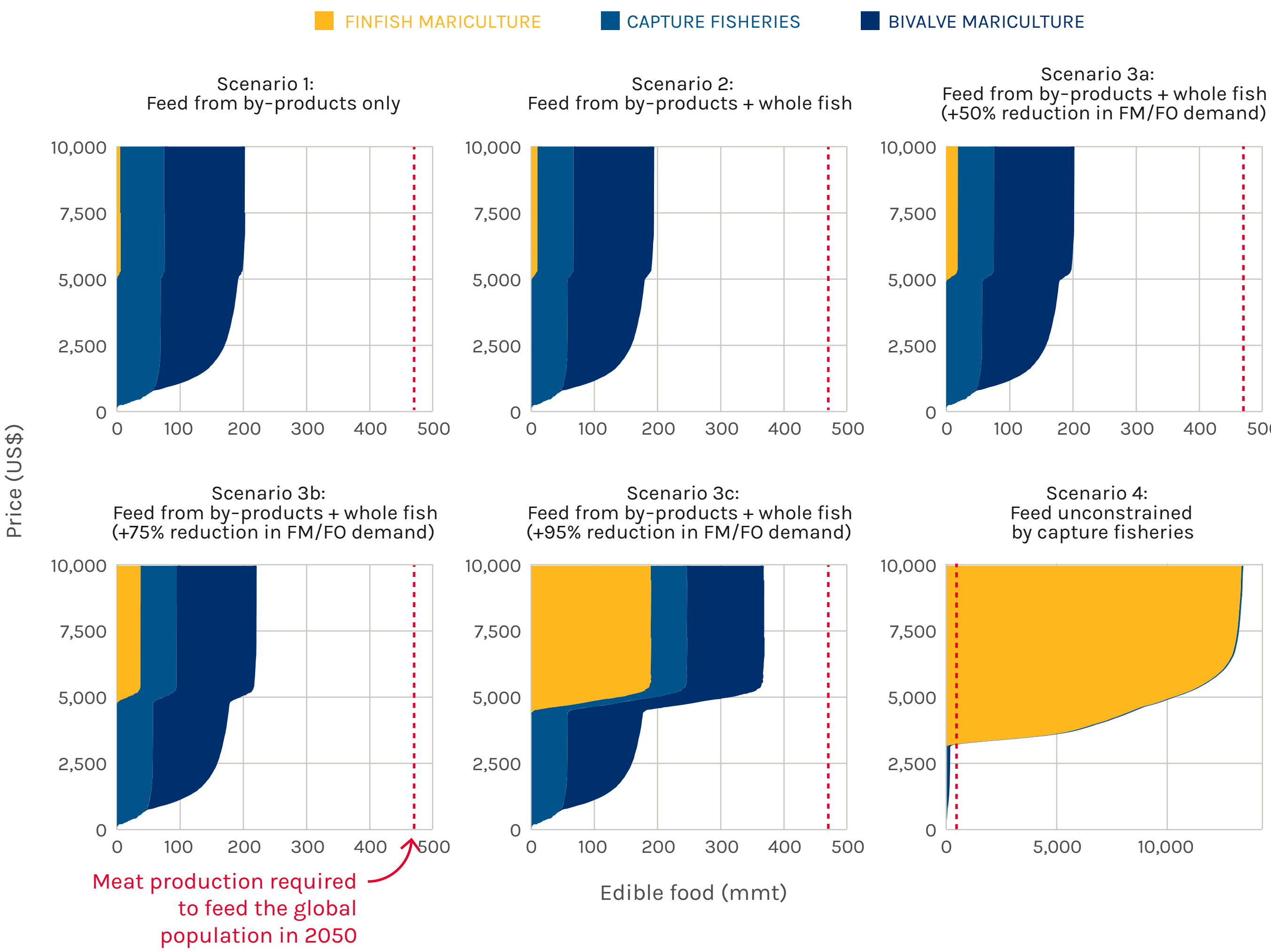
The largest gains in production of food from the sea will come from mariculture expansion, but production potential is currently challenged by FM/FO availability. In the absence of feed alternatives, bivalve mariculture has the greatest potential to contribute to food supply. Figure 4 shows the aggregate supply curves for bivalves (purple), capture fisheries (teal) and finfish mariculture (yellow) under the six scenarios presented above. Production values represent edible meat in million metric tons. Raw landings were converted into edible meat using conversion ratios in Edwards et al. (2019). Under Scenario 2, which mostly closely aligns with current FM/FO availability and feed requirements, finfish production is greatly limited and not profitable until the price exceeds $5,000 per mt. In Scenarios 1–3b, bivalve mariculture dominates as having the greatest potential production. However, the results suggest that the greatest potential for food production from the sea is from fed mariculture, assuming that production does not rely on FM/FO. This highlights the importance of affordable FM/FO substitutes for increasing the production of fed mariculture. In this scenario (4), in which production is limited only by the suitable space available for mariculture operations, total production is over 15 times that of Scenario 3c, which assumes that the fish oil component of feed formulas is reduced by 95 percent. The results suggest that a significant shift to feed alternatives is needed for finfish production to substantially expand: production potential for bivalves is still greater than that of finfish in Scenario 3b, which assumes that the fish oil component of feed is reduced by 75 percent. This suggests that in the absence of feed alternatives, bivalve mariculture has the greatest potential to contribute to food supply.

The ecological limits of forage fish production could challenge the growth of fed mariculture and the ability of the sector to meet demand. Froehlich et al. (2018b) find that future demand for fed aquaculture could be met through a combination of fisheries reforms, improved usage of fishery by-products, reduced use of forage fish in non-carnivorous species in all food sectors and continual improvement in animal efficiencies. However, the study similarly finds that reliance on forage fish may affect aquaculture growth, and that a sustained, rapid and more certain aquaculture future will depend on adequate alternative feed sources.

Others have estimated that in 2050 470 million metric tons of meat will be required annually to feed the projected global population of more than 9.1 billion (FAO 2009). Our supply curves suggest that under optimistic projections regarding alternative mariculture feed innovations and uptake, the ocean could provide 364 mmt of food annually (Scenario 3c, price equals US$ 5,500). This is over six times current capture and mariculture production (58 mmt of edible food[14]) and more than two-thirds of the edible meat that the FAO estimates will be needed to feed the future global population. This production is only possible if finfish mariculture is not dependent on feed made from fish products from capture fisheries.

14. Current edible food from the sea calculated using FAO capture fisheries and mariculture production information and conversion rates from Edwards et al. 2019.

Figure 4. Combined Supply Curves for Capture Fisheries and Mariculture under Four Feed-Constraint Scenarios



Note: In Scenario 1, feed for finfish mariculture is derived from only the by-products of capture fisheries. In Scenario 2, feed for finfish mariculture is derived from both reduction fisheries and the by-products of non-reduction fisheries. In Scenario 3, feed for finfish mariculture is derived from both reduction fisheries and the by-products of non-reduction fisheries with a (a) 50%, (b) 75% and (c) 95% reduction in the FM/FO demands of feed due to technological advances. In Scenario 4, feed for finfish mariculture is no longer constrained by capture fisheries due to the replacement of fish ingredients with alternative ingredients with technological advancements. Vertical dashed lines indicate an estimated 470 mmt of meat production required to feed the global population in 2050 (FAO 2009).

Source: Supply curve estimates are from Costello et al. (n.d).

5. Food from the Sea's Contribution to SDG 2

Although the number of undernourished people has decreased in recent decades, 821 million people are still considered to be undernourished, and hunger continues to be a challenge in many countries, particularly in rural or developing areas (UNDP n.d.; FAO 2018). To help address this, one of the UN Development Programme's Sustainable Development Goals (SDGs) is to end all forms of hunger and malnutrition by 2030 (UNDP n.d.). Seafood could play an important, and possibly pivotal, role in meeting SDG 2 by contributing highly nutritious sources of multiple, quite bioavailable nutrients and thereby improving food and nutrition security.

Food from the sea is uniquely poised to contribute to food security because it contains essential omega-3 fatty acids and highly bioavailable micronutrients that are crucial to a healthy diet

Food from the sea is uniquely poised to contribute to food security because fish is a highly efficient form of protein—150 grams of fish provide 50–60 percent of an adult's daily protein requirement (FAO 2018). And in addition to protein, fish products and seaweed contain essential omega-3 fatty acids and highly bioavailable micronutrients (vitamins A, B12 and D, as well as calcium, iron, iodine, zinc, selenium, phosphorus and zinc) that are crucial to a healthy diet (Kawarazuka and Béné 2010; Allison et al. 2013; Thilsted et al. 2016; FAO 2018).

In developing regions, seafood (freshwater and marine sources) provides a cheap and locally available food source (FAO 2018; Kawarazuka and Béné 2010). Seafood could play a particularly significant role in addressing hunger in Asia—which accounted for nearly two-thirds of the world's hungry in 2017—since that continent is home to the major marine capture and aquaculture producing countries. China's capture fisheries show a comparatively large potential for increased harvest with improved management (Costello et al. 2016). The expansion of aquaculture has allowed fish products to remain accessible to low-income consumers by limiting price increases for capture fisheries and keeping prices for farmed fish from growing as fast as those for other food sources (Belton and Thilsted 2014). However, rising demand for seafood (freshwater and marine sources) driven by population and income growth drives price increases (Naylor 2016). Because the countries most dependent on food from the sea and most vulnerable to nutrient deficiencies are low-income nations, accessibility for these populations will be particularly influenced by prices. Policies that encourage mariculture production of nutritious and affordable species and support low-income producers can help improve accessibility and food security (Naylor 2016).

Potential annual production from the sea is much greater than the estimated 470 mmt of meat needed to feed the population in 2050. This result is driven mostly by the potential for mariculture expansion, highlighting the importance of establishing policies that promote the sustainable development of mariculture production and finding a low-cost alternative for FM/FO. This line of reasoning seems to suggest that expanding fed mariculture will increase global food supply. However, fed mariculture relies on food-grade terrestrial crops and wild fisheries for feed ingredients, so the net effect is less clear. Further complicating this calculation, there may be important regional implications to such diversion as some countries rely on forage fish for inexpensive animal protein (Alder and Sumaila 2004) and may be able to more efficiently use agricultural products for DHC. See Section 8 for a more detailed discussion regarding the trade-offs between food for DHC versus IHC.

Although their production potential is smaller than that of mariculture, failure to improve the management of existing capture fisheries could limit production in the regions that most need strengthened food security. Unassessed fisheries are believed to be on average overfished and are mostly located in developing nations particularly reliant on fish for nutrition (Costello et al. 2016; Golden et al. 2016). A recent study estimates that 845 million people (11 percent of the global population) are at risk of undernourishment if fisheries continue to decline (Golden et al. 2016). Furthermore, climate change is expected to exacerbate challenges in developing countries in tropical latitudes, as fish stocks in this region are projected to decrease in productivity and shift to higher latitudes (Cheung and Pauly 2016; Cheung et al. 2013; Gaines et al. 2018; Pinsky et al. 2013).

Increased production can generate new and expand existing economic activities in coastal communities. For example, increased production of fish for food may lead to increased employment opportunities in the seafood processing sector. For more information on how ocean food provision is related to ocean economies, see Blue Paper 8, “National Accounting for the Ocean & Ocean Economy”.

6. Demand and Consumer Preferences

6.1 Demand Projections

Seafood[15] consumption per capita has more than doubled since 1961 and is projected to increase with rising population and affluence. As incomes rise and the population grows, the demand for seafood also increases. Global fish consumption has increased by 3.2 percent per year since 1961, which is twice the pace of the global population increase over the same time period (FAO 2018). Between 2008 and 2013, fish consumption increased by 20 mmt, where the primary drivers of change were increased population and incomes (representing 40 percent and 60 percent of increased demand, respectively) (Cai and Leung 2017). Total global consumption of seafood is projected to increase by 20 percent (30 mmt) by 2030, with the majority of increased demand coming from developing nations in Latin America, Africa, Oceania and Asia (FAO 2018). Demand is estimated to increase by 47 mmt by 2025, suggesting a supply-demand gap (Cai and Leung 2017).

6.2 Consumer Preference

The type and quantity of food from the sea produced in the future will depend not just on production potential but also on consumer preferences. The quantity of particular fish purchased in markets depends on income, prices and preferences. In many developing countries, consumption is influenced more by local supply, while consumption in developed regions is driven by preferences for products that are often produced elsewhere (FAO 2018). Cultural preferences are also an important driver of demand for food types. This interaction of supply and demand implies that seafood production that results in the greatest amount of food at the lowest cost will not necessarily result in increased consumption. Put differently, while we may be able to dramatically increase seafood supply at relatively low cost, the form of that seafood may not coincide with people's preferences, which would limit its uptake in the market.

Forecasting preferences is challenging. Preferences for seafood, both generally and for specific species, have shifted historically. Bluefin tuna was once regularly discarded (Pauly 1995), halibut was thought to be 'unpalatable' (Jacquet and Pauly 2007), and jellyfish had a very limited market in Asia until recently (Pitcher and Pauly 1998).

Concerns regarding food safety affect the demand for seafood products. Contamination risks are discussed in greater detail in Section 7.7.

6.3 Substitutability

To what extent are consumers willing to substitute fish for land-based meat? Available information suggests that fish is only a weak substitute for terrestrial meat (1 percent increase in the price of terrestrial meat leads to 0.04 percent increase in fish consumption in low-income countries, which are typically the most responsive to price changes) (Cornelsen et al. 2015). Even across different seafood products (e.g. across wild vs. aquaculture for the same species), substitutability is uncertain. However, species pairs may be complements or substitutes depending on the context and, in principle, the salient properties of the good (Wessells and Wilen 1994; Singh et al. 2012). Limited information suggests that aquaculture and capture fishery products may be to some degree substitutable (Asche and Sigbjørn 2005; Mickwitz et al. 2002).

15. In this section, "seafood" refers to aquatic foods from freshwater and marine environments.

6.4 Influences on Purchasing Behaviour

There is some evidence that marketing mechanisms can affect seafood purchasing behaviour. Marketing mechanisms that have been employed for seafood products include appealing to health benefits, eco-labelling and rebranding. Evidence suggests that consumers are becoming more concerned about the health of their diet (Lem et al. 2014; Röhr et al. 2005), and seafood consumption has been shown to increase alongside concern for healthy eating (Trondsen et al. 2004). While most studies report that consumers are interested in nutritional information, only some studies suggest that nutritional information actually changes purchasing behaviour (Grunert and Wills 2007). There is some evidence that health information can promote certain types of fish species over others. In a 2008 study, providing information about omega-3 fatty acids and methylmercury to consumers induced a shift away from canned tuna to sardines (Marette 2008).

The effect that eco-labels may have on purchasing behaviour is unclear, with positive effects seen on tuna consumption from the implementation of 'dolphin safe' labelling in the United States and no effect seen on efforts in Asia (Cai and Leung 2017).

Some rebranding efforts appear to have increased demand for certain seafood products. Marketing efforts to rebrand slimeheads as orange roughy and Patagonian toothfish as Chilean seabass successfully increased demand, but potentially not without important biological consequences—both species are classified as 'avoid' by Seafood Watch, suggesting that some of these stocks may be or may have been overfished or may be experiencing overfishing (Seafood Watch n.d.b; Seafood Watch n.d.a). In addition, salmon is now used for sushi around the globe after the success of a Norwegian marketing initiative for farmed Atlantic salmon despite the fact that salmon traditionally was not consumed as sushi (All Things Considered 2015).

Removing informational barriers about aquaculture may increase consumer demand for farmed products. Aquaculture demand has likely been limited because of concerns by consumers, governments and various industries (FAO 2018; Mazur and Curtis 2006). Informed critics often point to the unknown or unappetising social, economic and environmental implications of mass mariculture (Mazur and Curtis 2006). Improving the perception of aquaculture may increase demand and allow for further development of the technology as a means of low-cost protein production (Gempesaw et al. 1995), though this may involve improved communication regarding the real versus perceived impacts of aquaculture (Froehlich et al. 2017b).

Greenwashing has the potential to shift preferences towards products that are not sustainably produced and result in environmental degradation. Greenwashing is marketing with the intention of giving the false impression that products are environmentally friendly. Such marketing may have important environmental consequences and negatively impact truly sustainable efforts.

7. Other Considerations

7.1 Ensuring Management Capacity

Given the diversity of ecological, political and socioeconomic systems where fishery management and mariculture alternatives may be applied, the successful design and implementation of measures to ensure that the ocean plays its potentially important role in global food production is a complex endeavour. Addressing the real-world constraints of actual governance contexts such as fragmented institutions, contested policy processes (Jentoft and McCay 1998), and poorly delineated roles and capacities of policymakers (Gelcich et al. 2019) and administrators is critical (Patterson et al. 2017). In addition, providing technical support for management decisions requires analytical skills to design monitoring programs, assess the status of resources and adjust management strategies.

Fishery and mariculture innovations aimed at securing seafood necessarily imply the redefinition of management goals, the establishment of new roles for existing actors and the structuring of new decision-making processes (Moore et al. 2014; Gelcich et al. 2019). This entails responding to important challenges associated with national and local capacity to implement changes legitimately. Capacity building, both institutional and technical, is needed in many countries in order to move from current trajectories towards the sustainable supply of seafood. This includes support for the design, implementation, monitoring and institutionalisation of novel management regimes. These capacities should include ecological as well as social and governance dimensions (Cinner et al. 2014). In addition, capacity-building instances should be designed to be adaptive and iterative in order to maximise learning (Berkes et al. 2000).

Innovation to secure sustainable seafood supply is arguably of limited utility if it is not applicable, due to capacity or other constraints, to the local and national conditions where a program is being targeted. Measures inappropriately applied in different settings could even have negative impacts (Fulton et al. 2011). Developing the necessary capacity through place-based research is needed for success, along with guiding principles and methodologies that assure best practice. The development of communities of practice and regionally based learning platforms which build capacity to design and implement novel fishery and mariculture policies and programs would likely improve outcomes (Gelcich et al. 2010). By broadening capacity building to also include social and governance dynamics, countries will also be better positioned to support the design, implementation and monitoring of novel sustainable seafood programs (Kittinger et al. 2013).

7.2 Markets and Trade

Trade will play an important role, and possibly a crucial one under climate change, in ensuring global food security and increasing availability and consumption of food from the sea. Seafood products (marine and freshwater) are widely traded across the globe, and rates of international trade have been increasing in the past decades—in 2016, 27 percent of all fisheries and aquaculture production for direct human consumption were traded (FAO 2018). Trade will become increasingly important for countries and regions for which climate change reduces local productivity and availability of seafood resources. Exporting countries may experience a number of challenges when trying to access global markets, including low-quality fish products due to inadequate infrastructure (see Section 7.4), as well as measures that are expensive or difficult to comply with or obtain proof of compliance for (FAO 2018). Developing nations, which are exporting fish products at a faster rate than developed nations, may be the most susceptible to international trade challenges (FAO 2018). The overall effect of fish trade in terms of local food security and improved livelihoods is unclear (Béné et al. 2010), and the implications of trade dynamics should be carefully considered when developing relevant policy.

7.3 Climate Policy

Expected impacts on both capture fisheries and mariculture will depend on future emissions, and the full extent of these effects is unclear. The full effect of climate change on potential food production from the sea is made uncertain by the wide range of potential climate effects and the difficulty of modelling these complex interactions. Ocean acidification interferes with the growth of calcium carbonate shells and skeletons, which is expected to directly affect commercial shellfish species. Ocean acidification may also indirectly affect harvests of shellfish predators and species that rely on coral reef habitats (Cooley and Doney 2009). The alteration of species composition by spatial shifts may result in predator-prey dynamics that are difficult to account for in global modelling exercises. Pests and pathogens, which can affect both capture and mariculture production, may change or become more prevalent with climate change (Barange et al. 2018). In addition, extreme rainfall events may increase the flow of nutrients and chemicals from land-based systems to coastal environments, where they can affect the availability of nutrients, hypoxia levels and sedimentation, and thus fish productivity. For more information regarding climate change impacts on fisheries and other ocean economies, see Blue Paper on "The Expected Impacts of Climate Change on the Ocean Economy".

Climate policy should address climate and fishery management simultaneously (prevent RCP8.5). Although the full extent of climate impacts is uncertain, a number of measures can increase resilience to climate effects on fisheries. First, implementing adaptive harvest strategies that reduce fishing pressure as fish stocks become less productive can help ensure that fish stocks are not fished beyond their biological limit and allow overfished stocks to rebuild (Melnychuk et al. 2014). Second, effective transboundary institutions can help prevent overfishing as fish stocks shift across jurisdictions. A recent study found that implementing these two strategies together could lead to more harvest globally in 2100 than what is experienced today for all but the most extreme RCP projection (RCP8.5), despite projected global decreases in MSY (Gaines et al. 2018). Because this result cannot be attained under high climate change (RCP8.5), greenhouse gas emission mitigation will be important for reducing the potential negative climate effects on fishery production (Gaines et al. 2018).

7.4 Insufficient Infrastructure

Many countries lack the infrastructure needed to preserve fish quality for human consumption, but this must be expanded with care. Examples of marine infrastructure that affect food provision include hygienic landing locations, sufficient power supply, potable water, ice, cold storage, roads, refrigerated transportation and processing facilities (FAO 2018). Cold storage is particularly important in tropical regions, where high temperatures can cause fish to spoil along the supply chain. It is estimated that post-harvest losses due to insufficient infrastructure can reach up to 50 percent, 70 percent of which is due to deterioration (Akande and Diei-Ouadi 2010). Despite these needs, expanding infrastructure in places with poor fisheries governance or open access conditions will likely result in further depletion of fish stocks and ultimately worse outcomes for fishers (Cabral et al. 2018).

7.5 Harmful Algal Blooms

Harmful algal blooms (HABs) (i.e. 'red tides') are large concentrations of microscopic algae. These blooms can be stimulated by sewage, runoff/discharge from agriculture or aquaculture, or atmospheric deposits (Anderson et al. 2002). Toxic algae can harm marine life through the transfer of toxins, while non-toxic algae can affect marine life through habitat alteration, oxygen depletion and displacement of species (Anderson 2009), which can affect both wild and farmed fish (Shumway et al. 2018). Incidences of HABs may increase with warming sea-surface temperatures (Barange et al. 2018). In May 2019, more than $82 million worth of farmed salmon suffocated in an HAB (Magra 2019). Due to constrained movement, farmed fish or shellfish is more likely than wild species to be affected by HABs.

7.6 Habitat Degradation and Pollution

Habitat can be degraded by activities within and outside of the fishing sector, such as coastal development, oil spills and greenhouse gas emissions. Dynamite or blast fishing destroys coral habitat and can decrease fish populations (Young et al. 2016), while mariculture operations, if not carefully maintained, can result in chemical and nutrient pollution from therapeutants and other inputs, posing risks to environmental and human health. Coastal development can degrade important habitats through activities including dredging and construction, as well as through increased chemical or nutrient pollution (Pandolfi et al. 2003; Crain et al. 2009). Changing of river runoff or influx and development of hydroelectric dams can impact diadromous fish populations (Larinier 2001). Plastic and microplastic pollution, which originates both within and outside of the fishing sector, can negatively impact fish resources directly (e.g. entanglement and ingestion of contaminants) and indirectly (e.g. gas exchange blocked by debris accumulation, resulting in hypoxia or anoxia; habitat alteration) (Derraik 2002). Climate change may also result in habitat degradation through ocean acidification (leading to coral bleaching), sea level rise, increased storms and potential increased occurrence of harmful algal blooms (see Section 7.5 for more information regarding HABs). All of these factors can compromise food safety and the health of food from the sea. For more information on how pollution affects marine environments, see Blue Paper on “Pollution and a Regenerative Economy: Municipal, Industrial, Agricultural, and Maritime Waste, Its Impacts and Solutions”.

7.7 Food Safety Concerns

In order for food from the sea to meaningfully contribute to future food supply and SDG 2, seafood must be safe to consume. Hazardous chemicals and heavy metals can bioaccumulate in fish and bivalves, leading to worries over the safety of consuming seafood products (Jennings et al. 2016). Filter-feeders can accumulate marine biotoxins that naturally occur in phytoplankton and HABs, as well as pathogens that pose risks to human health. This is a particular concern for the production potential of unfed mariculture (Jennings et al. 2016). Microplastic accumulation in fish may also pose a risk to human health. The human health effects associated with consuming seafood containing microplastics are unclear, and more research is needed to assess the potential threats of such contamination (Barboza et al. 2018).

8. Trade-Offs

Policies to ensure and enhance ocean food provision can sometimes be win-win, but they will often require trade-offs. As with any policy decision, policymakers should consider the pros and cons associated with different options, as well as those associated with inaction versus action. Below we describe seven key trade-offs related to food from the sea.

8.1 Using capture fisheries production for indirect versus direct human consumption

Currently, about 18 percent of capture landings are ultimately used not for human consumption but to produce fishmeal and fish oil (FM/FO). These products are used as ingredients in terrestrial animal and aquaculture feeds. Fisheries used for indirect human consumption (IHC) tend to be small pelagic species such as anchovy, sardine and herring. The FM/FO produced by these fisheries are often exported from the country in which they were fished. Some have argued that these fish should be used for direct human consumption (DHC) in the countries where they are harvested because they are highly nutritious (e.g. contain long chain omega-3 fatty acids and vitamin B12) and therefore could contribute to local food and nutrition security, and reduce national malnutrition. Indeed, in many regions, these small fish are regularly consumed and contribute to nutritional needs.

However, market dynamics may preclude IHC fisheries from contributing significantly to food production. In other words, food security might be better served by using these fish for FM/FO rather than for direct human consumption. First, the global demand for FM/FO likely surpasses that of forage fish as food. An important barrier to consumption is consumer preferences. Peru used marketing campaigns in an effort to increase demand for anchoveta, which is almost exclusively destined for the reduction sector, as food. However, it seems that these efforts have failed to significantly shift preferences. It is also important to consider the economic trade-offs associated with restricting the use of capture fisheries in the reduction industry. For example, such restrictions may result in lower profits for fishers because of the comparatively high price of FM/FO, which may affect their ability to purchase the food items that they wish to consume.

Replacing FM/FO from wild caught fish with alternative feed ingredients may compromise some of the aspects that make food from the sea a uniquely promising contributor to food security. First, nutritional benefits from fed mariculture may be undermined as FM/FO is replaced by terrestrial crop products in feed, as these alternatives lack the omega-3 fatty acids important for fish and human health. Second, many feed alternatives are comparatively expensive, and thus their use in feeds may increase prices for mariculture products and other foods, reducing accessibility for low-income populations (Troell et al. 2014). There have been major improvements in feed efficiency, and the potential for other sources to replace forage fish as feed ingredients is currently being explored. We discuss these alternatives in Section 3.4.

Fisheries management for capture fishery resources that are used for FM/FO production will be critical to ensuring environmental and economic sustainability as well as food security. An estimated 63 percent of all wild-caught forage fish are used specifically for aquaculture feed and account for upwards of 1 trillion fish taken from the ocean annually valued at S17 billion (Pikitch et al. 2012). Forage fisheries must be carefully managed to avoid overexploitation given the demand for feed from the aquaculture industry, as they play an important role in marine food webs, supporting fish higher up on the food chain, as well as seabirds and mammals. Fishing these populations to unsustainable levels could result in highly altered fish populations, marine food webs and marine habitats.

In addition, small fish of low economic market value are also used as feed in aquaculture. These harvests, unlike those from fisheries explicitly developed for IHC, often come from untargeted fisheries and include species that have commercial value as food but are undesirable for the direct food market (e.g. they may be undersized). These harvests can have important biological implications for fish stocks that provide food. Managing these stocks may result in an increase in volume that can be directed towards food provision, but it would also result in decreased availability of these fish for use in aquaculture. There are important cultural differences around the world in the way these fish are viewed by consumers, so local context must be accounted for when designing management interventions that affect these products.

8.2 Using terrestrial crops for IHC versus DHC

Formulas for aquaculture feed increasingly rely on food-quality terrestrial crops (Tacon and Metian 2015; Aas et al. 2019; Troell et al. 2014). Although one could argue that food-grade crops could more efficiently contribute to food supply through DHC, the aquaculture industry uses just 4 percent of land-based crops utilised for animal feed, while the rest are used for terrestrial animal production (Froehlich et al. 2018c). This demonstrates the comparatively large pressure that terrestrial animal production places on the agricultural sector and the relative efficiency of using feed for aquaculture production (Froehlich et al. 2018c).

8.3 Unfed mariculture versus fed mariculture

In this report, we discuss the differences between unfed and fed mariculture production. Unfed mariculture does not rely on feed inputs and therefore does not put as much pressure on other resources (e.g. land and freshwater needed to cultivate agricultural-based feed ingredients) as fed mariculture. In addition, it does not rely on food-grade products (e.g. agricultural products and capture fisheries) that could otherwise directly contribute to feed supply. However, fed mariculture produces high-value species, suggesting that there may be greater demand for fed mariculture products than for the DHC of the crops and fish that compose their feed. Increasing fed mariculture production will require increases in feed availability driven by alternative ingredients.

8.4 Economic costs versus sustainable production in mariculture

As outlined above, mariculture production entails a number of potential negative environmental impacts. Many of these, including disease and parasite outbreaks, chemical and nutrient pollution, and habitat loss, can be addressed by approaches and technological advances described in Table 3. However, these options are often more costly to producers, and their adoption could make a now-profitable operation unprofitable. Even when these ultimately benefit mariculture production and profitability, there may be important incentive challenges to overcome, in a manner similar to what we find in sustainable agriculture. Measures to incentivise mariculture producers to adopt more sustainable approaches and materials include the following:

- Establishing environmental standards (e.g. water quality standards) that are measurable. Monitoring conditions and enforcing standards with reasonable penalties.
- Pricing environmental externalities into production.
- Providing financial incentives for research and technological innovations.

8.5 Marine seafood compared to other food sources

How does food from the sea stack up against alternative food sources?

Aquatic versus terrestrial animal-source food

Average overall food production from terrestrial animal sources (beef, buffalo, pigs and poultry) for 2011–15 was three times higher than total edible production from aquatic sources (crustaceans, finfish and molluscs from aquaculture and capture fisheries) (Edwards et al. 2019). The highest production was from pigs and poultry (115 and 110 mmt, respectively), followed by aquatic food (i.e. capture and aquaculture fisheries) at 98 mmt combined, with beef contributing 68 mmt (Edwards et al. 2019).

Mariculture, particularly for fed species, can be subject to many of the same environmental and health concerns that arise in terrestrial husbandry, including chemical and nutrient pollution, disease and parasite risk, dependence on inputs from other food sectors (in the case of meat production), and (although to a lesser degree) habitat conversion. Food safety can be a concern for food produced in the sea due to pollution and toxins. Mariculture operations do not compete for water and land resources for production sites in the same way that terrestrial food production does, and they have ample space to expand (although it is important to note that much of this space is not currently economically viable).

Mariculture versus freshwater aquaculture

Freshwater aquaculture occurs in controlled environments on land and therefore is often less expensive to operate, easier to control (e.g. in terms of targeted application of feed and antibiotics) and protected from ocean pollution. In addition, the potential for species interactions is limited in freshwater aquaculture operations. Many of the freshwater species that are farmed on land require less (or no) feed. However, the types of species that can be raised in freshwater aquaculture are limited, and their potential production is more limited due to land and water dependencies.

Mariculture versus capture fisheries

Because both exist in the same environment, mariculture and capture fisheries can be affected by ocean pollution (e.g. plastics, mercury, chemicals, toxins, nutrients). As discussed previously, capture fisheries can be affected by mariculture operations through chemical and nutrient pollution from farming operations, disease and pest transfer, antibiotic use, habitat destruction and interactions with escaped fishes. Capture fisheries are limited by biological and ecological constraints, whereas the potential for increased mariculture production is large.

Marine seafood versus cell-based seafood

An industry still in its infancy, cell-based seafood uses cells from fish products to cultivate sheets of muscle tissue in labs. Seafood grown in a lab environment is not subject to pollutants in the ocean or environmental changes from climate change. Unlike fed aquaculture, it does not require FM/FO to develop. Cell-based seafood's potential environmental impacts in terms of greenhouse gas emissions and dependence on terrestrial crop inputs (e.g. sugar) is unclear, as is its potential to capture part of the seafood market, and possibly contribute to ecosystem restoration as consumers switch. More research is needed on the potential of cell-based seafood to understand its potential contribution to global food supply.

Seafood consumed locally versus exported

Trade plays an important, albeit complex, role in the availability of fishery products around the globe. Some have argued that countries would be better off not exporting seafood products and instead consuming them locally (Béné et al. 2010). However, trade dynamics can be nuanced. For example, while Africa is a net exporter in terms of value, it is a net importer in terms of volume, suggesting that regional food security benefits from trade flows (FAO 2018).

8.6 Large-scale production versus environmental quality

Significant expansion of food production from the ocean is currently costly. Mariculture has much greater production potential than capture fisheries, but generating this production is expensive. In order to bring costs down, mariculture farming approaches will need to be scaled and intensified similarly to terrestrial food production systems, which has important environmental consequences. Policymakers will need to weigh the benefits and costs associated with making mariculture production financially feasible. No production system can have zero environmental impact, and it is important to assess the relative costs and benefits associated with food production options (including the decision of inaction).

9. Identifying, Evaluating and Implementing Reforms

The purpose of this Blue Paper has been to examine the role that the ocean currently plays, and could play in the future, in providing sustainable food from the sea. How great this role can be will depend on both the supply and demand for ocean-based food products. On the demand side, animal protein will be increasingly sought after as incomes rise, and as the global population expands (FAO 2018). Our analysis focuses on the supply side, where we find that the overwhelming majority of future global production potential from the sea comes from mariculture. However, our study also reveals that production potential depends on prices, production costs and fishmeal and fish oil (FM/FO) feed requirements, which currently constrain the amount of food that can be produced from mariculture. Prices will also partly determine which populations of people are able to access the farmed products. Scaling mariculture operations could result in substantial increases in food production, and management practices that limit environmental degradation will help promote long-term benefits from this and connected sectors while simultaneously protecting human health. With improved fishery management, capture fisheries also have the potential to produce more food, and this would bring other co-benefits such as higher fishery profits, lower ecosystem degradation and higher biodiversity. But potential increases in food from capture fisheries are significantly smaller than those from mariculture: with improved management capture fisheries could generate about 20 percent (13 mmt) more food than current production levels, but their maximum sustainable production potential for edible food is biologically and ecologically limited to about 71 mmt (Costello et al. n.d.). This potential is likely to be dwarfed by mariculture, particularly as new feed technologies are developed.

> Designing effective policy interventions regarding the future of food from the sea will depend on a country's objectives and constraints

Production potential and other considerations related to food security (e.g. accessibility) varies substantially across countries. Barriers and challenges to increasing production, such as overfishing and climate change effects, also affect countries differently. Consumption will also vary among regions and populations due to differences in price, preferences and income.

Because economic, ecological and food security conditions differ across countries, and because food-focused interventions also have other consequences (e.g. for conservation and economic output), there is no one-size-fits-all prescription for enhancing food from the sea. Rather, designing effective policy interventions regarding the future of food from the sea will depend on a country's objectives and constraints, including constraints on capacity (e.g. technical, administrative, governance), finances and production potential due to environmental limitations. Below we outline a framework of five steps that policymakers and scientists can use to inform regional decision-making regarding food from the sea.

1. Clearly define objectives and priorities in the ocean.

Effective interventions will require a clear understanding of a country's objectives and priorities. While some ocean interventions are specifically tailored for a particular objective (e.g. large Fully Protected MPAs are often designed to benefit biodiversity and ecosystem protection), others simultaneously address multiple objectives (e.g. ending overfishing can address food production and fishers' livelihoods). When market failures are severe, some management interventions can even achieve a 'triple-bottom-line', resulting in increased biomass in the sea, food production and profits.

Therefore, before attempting to design effective interventions, it is critical that policymakers define their objective(s). Examples of potential objectives include maximising food production, delivering food security to vulnerable populations of people (e.g. accessibility of food products), supporting the livelihoods of fishers or other groups and advancing conservation. To be useful, these objectives must be measurable; that is, there should be a way to measure how well any intervention has achieved the stated objectives.

Interventions will have different effects on diverse stakeholders, thus it is important to consider their distributional impacts. For example, if the objective is to maximise fishery profits from a country's capture fisheries, then findings in the literature suggest that implementing rights-based fisheries management is an intervention that is consistent with reaching this goal. While this intervention may result in the highest fishery profits, the distributional effects across diverse stakeholders will depend on how the intervention is designed. If this second criterion (distributional equity) is ignored in program design, then the intervention is likely to only achieve the first, explicitly stated, objective (of maximising profit). This observation reveals another important principle: all relevant objectives should be stated at the outset; those left unstated are unlikely be achieved.

2. Conduct assessments of resource status.

After the objectives have been clearly articulated, we recommend that a country conduct an assessment of the status of food from the sea in its waters. Where possible, this could be benchmarked against theoretical potential under realistic ecosystem constraints, as has been done at a global level in this report. This status assessment should be completed for both the capture and mariculture sectors.

Data collection is an important component of performing this assessment, as our understanding of the current status and ability to manage for stated objectives can improve with accurate information. In contexts for which managers are unable to collect sufficient data for more sophisticated assessments, data-poor assessments can be used to estimate the current status of resources.

In addition to data availability, the type of assessment that can be implemented will depend on technical capacity and funding. While outside expertise can be brought in to conduct assessments, governments often find it in their long-term best interest to develop local capacity to conduct these assessments. This process, as well as data collection and performing assessments, require funding and therefore typically government support. In some countries, management costs (including those spent on data collection and performing assessments) are partially or fully recovered by the fishing industry through cost-recovery systems.

Considerations for capture fisheries:

Stock assessments determine relevant reference points (e.g. B_{MSY}, F_{MSY}; see Section 2.1), as well as current status relative to those benchmarks. The majority of the world's wild fish stocks, representing about half of global fish catch, lack formal stock assessments, and therefore their status is unknown (FAO 2018; Costello et al. 2012, 2016; Ricard et al. 2012; Hilborn and Ovando 2014). The results of data-poor approaches estimate that most of these stocks are overexploited and experiencing overfishing (Costello et al. 2016). Governments with policy objectives related to capture fisheries should determine for which fisheries the status is known and, depending on policy objectives, which fisheries should be assessed. Fishery management is not free, and managers can prioritise fisheries based on their objectives. For example, if the primary goal is maximum food production from capture fisheries, then managers should focus assessments on those fisheries with the greatest potential for food production (e.g. high-volume fisheries). This ranking of fisheries may differ from the ranking according to, say, ability to produce the greatest fishery profit (e.g. for high-value, low-volume species). Instead, if the objective is to provide food security for self-sufficient coastal populations, then assessments would likely focus on smaller, coastal fisheries.

Considerations for mariculture:

This report demonstrates that the future production potential of mariculture is much greater than its current production. Like assessments for capture fisheries, the basic idea behind a mariculture assessment is to determine the extent of mariculture in a country relative to its potential. This assessment may involve suitability assessments that examine species, locations, associated costs of production and risks, all viewed relative to global prices for those species. Risks can be financial (e.g. infrastructure damage from storms), environmental (e.g. disease, pests and parasites, and harmful algal blooms) and social (e.g. food safety concerns associated with HABs, dependence of farmed species' nutritional quality on feed ingredients). Because governance and property rights are central to the expansion of mariculture, a review of these institutions would be prudent.

3. Evaluate intervention options.

Once assessments of the status, trends and potential for capture fisheries and mariculture have been completed, governments and managers should evaluate the pros and cons of intervention options. Modelling is a useful tool for simulating and comparing the results of intervention options. By evaluating modelled outputs against the stated objectives, one can assess the effectiveness of different intervention options. For example, such models could be used to compare the food provision consequences of a marine reserve versus an anti-illegal fishing policy. To provide useful outputs, models should be designed to account for all important aspects of the given system. For example, if the model ignores important ecosystem linkages, such as predator-prey dynamics, then it will be hard to evaluate interventions with strong ecosystem effects, such as reducing fishing of a low-trophic-level species.

Considerations for capture fisheries:

In this report, we outline the pros and cons of management approaches that could, in theory, be used to achieve food-related objectives such as maximising production at MSY (Table 1). Here, we discuss how three prominent interventions may help achieve, or relegate, various objectives.

Rights-based fishery management (RBFM):

RBFM is a collection of approaches including territorial use rights for fishing (TURFs), individual transferable quotas (ITQs) and fishery cooperatives. RBFM approaches assign exclusive rights and responsibilities to individual fishers, communities or cooperatives to fish in a given spatial area or to catch a given quantity of fish. They may be designed to promote various food-from-the-sea objectives because they provide a long-term incentive for resource stewardship, which is usually related to sustainable food provision. Generally speaking, area-based approaches (such as TURFs) have been primarily designed and implemented in small-scale, coastal fishery settings and can promote both food security and fishers' livelihoods. Catch-based approaches (such as ITQs) are usually implemented in larger industrial fisheries and tend to be designed for economic efficiency. Achieving other social objectives, such as equity across fishers and openness to new entrants, requires careful design. Relevant design considerations include the way rights are allocated to stakeholders (e.g. grandfathering, equal shares, auction), the permanence of the right (e.g. short-term, long-term), regulations regarding transferability (e.g. prohibited, restricted and fully transferable), and taxation of benefits, as each design option has environmental and social implications.

Marine protected areas (MPAs):

Fully Protected MPAs (i.e. marine reserves [MRs]) are areas of ocean off-limits to resource extraction. While this may seem contradictory to the idea of food provision from the sea, there is some evidence that appropriately sized Fully Protected MPAs could increase food provision in open-access settings (Cabral et al. 2019). Fully Protected MPAs can be used as a kind of substitute for fishery management to reduce overfishing, and, if designed well, could increase local food production for some species. At the same time, while Fully Protected MPAs may achieve a number of other objectives (such as ecosystem protection), they are likely to reduce food provision when implemented in fisheries that are well-managed or underfished (Hilborn et al. 2004; this highlights the need to conduct careful assessments (see Step 2 above). In addition, food benefits from Fully Protected MPAs may be precluded by the redistribution of fishing effort. A second setting in which MRs may benefit food from the sea is in conjunction with RBFM, where they may act as a 'bank' of fish, providing valuable larval export and spillover benefits to adjacent TURF- or ITQ-managed areas (Lester et al. 2016). For example, combining Fully Protected MPAs with TURFs (in so-called TURF reserves) may help buffer the TURF fishing community against fluctuations in food supply. New global data may allow for the spatial targeting of Fully Protected MPAs in the best sites for food provision benefits (Cabral et al. n.d.).

Conventional input controls (ICs):

Most fisheries around the world are managed not with RBFM or MRs but with a suite of input controls such as size limits, season limits and gear restrictions. Theoretical models suggest that it is possible for ICs to achieve food provision objectives. But empirical evidence suggests that fisheries managed with ICs are often overfished and therefore deliver less than their full potential of food from the sea. There are many reasons why ICs are likely to be overfished, despite the best intentions of fishery managers. First, even if inputs are carefully monitored, this provides no guarantee about the ultimate harvest of fish. Second, when users lack a long-term stake in the resource, they often 'capture' the regulator and lobby for less onerous regulations, resulting in ever-larger fish catch. And third, there are many margins of adjustment that fishers can make, so even if some inputs are well controlled, others will inevitably go unregulated. For these (and other) reasons, ICs are likely to fall short of a country's food-from-the-sea objectives. We recommend that countries carefully consider the shortcomings of ICs and evaluate possible alternatives, such as the approaches described above.

Considerations for mariculture:

Unlike the capture fisheries around the world, large-scale mariculture is an emerging sector, and sustainable and scalable interventions have only started to be implemented. Aquatic animals have yet to be farmed on the same scale as terrestrial animals, and the potential for technological and institutional innovation to scale production in a similar way (e.g. through selective breeding) is enormous (Edwards et al. 2019). Therefore, many interventions for this sector may look quite different from those in the capture sector. Here we examine four priorities that will help shape specific interventions in the mariculture sector.

Aquatic animals have yet to be farmed on the same scale as terrestrial animals. The potential to scale production is enormous

a. Property rights and other institutional innovations: If an especially innovative and efficient farmer seeks to grow strawberries, all he or she needs to do is purchase or lease a farm and start growing. The same is not true for mariculture. Most countries suffer from weak or non-existent property rights in the ocean and burdensome and confusing regulations. This ambiguity can lead to two possible outcomes. First, in many such countries almost no mariculture has been developed. While this outcome may please conservationists, it is hardly consistent with the results of this study, which suggest that sustainable mariculture could be one of the most ecologically sustainable forms of food production. Second, ambiguous property rights could lead to unsustainable overproduction of mariculture in some locations. In the long run, this also compromises food from the sea (e.g. when pests or diseases take hold). Thus, we recommend a careful evaluation of property rights and regulations regarding mariculture. While some regulations could be modelled on successful terrestrial examples, it will be important to identify where marine and terrestrial systems differ and design policies that effectively manage for those differences. Because mariculture production often generates many negative externalities (e.g. escaped fish and pollution spillovers between operations), policies that ensure producer responsibility will be important. Other possible interventions include spatial concession (with the possibility of renewal for good stewardship), TURFs, and clear regulations with sound monitoring and evaluation to ensure sustainability. As with other interventions proposed here, these should be designed in accordance with the objectives from Step 1.

b. Investing in feed technology R&D: The most significant constraint on food production from mariculture is that most valuable farmed species still require significant feed derived from capture fisheries (see Section 3.3 and Figure 4). While feed alternatives that could reduce mariculture's dependence on wild marine resources exist, they are generally expensive and have not been scaled for widespread adoption. Technological and institutional innovations will be key for finding adequate solutions to address the feed constraint, but one could argue that the public-good nature of such inventions limits innovation investment by the private sector. To the extent that innovations in feed technology would benefit society at large, this may justify enhanced public sector investment in alternative feeds.

c. Technological innovations that alter fish: Selective breeding and genetic modification of the species raised in mariculture may improve feed efficiency and disease resistance and thus reduce antibiotic use (Table 2) (Kim et al. 2019). These alterations may reduce dependence on feed that contains FM/FO and reduce environmental risks associated with antibiotic resistant disease strains. Again, to the extent that private investment will be insufficient because of public-good benefits, this may justify increased government investment.

d. Environmental and social implications of scaling: While the scope for increased production from mariculture operations is large, it is important to consider the environmental and social implications of scaling efforts. Lessons from terrestrial animal production could be applied to the ocean sector in an effort to minimise unintended and undesirable environmental consequences of certain farming practices. In addition, mariculture operations may have direct and indirect social consequences. For example, decisions regarding feed ingredients and the type of species to be farmed may affect nutritional content and accessibility (via prices), while operations that degrade the surrounding environment may affect other industries that rely on coastal or ocean resources. Another contemporary example is with cell-based seafood and other non-animal seafood alternatives, for which environmental, social and ecological impacts are not well understood.

4. Explicitly consider challenges and trade-offs.

Challenges and barriers to delivering sustainable food from the sea will vary from region to region, and effective interventions will vary accordingly. For example, the effects of climate change on capture fisheries and mariculture will vary spatially and temporally, and may have important implications for the design of effective interventions (see Sections 2.3 and 3.4). Climate change is likely to negatively impact capture and mariculture production potential in tropical countries, but mariculture may still be able to produce large amounts of seafood given its huge production potential. In such a setting, food security may be best-served by thoughtfully permitting mariculture, rather than relying only on (dwindling) capture fisheries. At the same time, even if climate change compromises wild fishery productivity, sound fishery management is still the best way to maximise food provision from any country's wild fisheries.

Considerations for capture fisheries:

One of the most salient threats to reaching production and profit potential in capture fisheries is overfishing (see Section 2.3). However, the degree of overfishing varies dramatically around the globe. Even if overfishing is not currently a problem in a country, without effective governance and policy, it may become a problem as economic or ecological conditions change. The incentives engendered by RBFM (see Step 3) can go a long way towards eliminating overfishing, but additional interventions such as MRs, eliminating capacity-enhancing subsidies, reducing IUU fishing, maximising compliance with existing rules and supporting relevant data collection and stock assessments can also play a role (see Sections 2.3 and 2.4). As countries design packages of interventions, we recommend that they carefully consider trade-offs—as one policy lever is pulled, how does it affect various objectives of interest?

Considerations for mariculture:

One of the greatest threats to mariculture expansion is the lack of clear rights, rules and responsibilities, which limits investment in feed and other animal husbandry technologies. Countries with great mariculture potential but little mariculture development may choose to develop a regulatory framework that allows for measured expansion. Expanding mariculture production without sufficient policies to protect human health and the natural environment, however, could result in undesired levels of pollution, risks to human health and environmental degradation. Thus, the decision of whether, and how, to expand mariculture is not a simple one. Policymakers should assess relevant trade-offs across identified objectives while designing policies for this emerging sector. Policymakers may also find important trade-offs between capture fisheries and mariculture, and prudent interventions will require careful consideration of these costs and benefits (see Sections 3.4 and 8, and Table 3).

5. Implement interventions that meet objectives and develop monitoring frameworks.

Once managers have evaluated potential interventions and compared the expected outcomes to policy objectives, we recommend that policymakers and managers design and implement the interventions that best meet their objectives. Governance and management capacity are critical for this step, which is why it is important to develop capacity at the relevant regional scale (see Section 7.1). Because the real-world consequences of these interventions are often uncertain, their effects should be monitored to assess whether they are indeed meeting the objectives as predicted and whether they are causing any unintended consequences. Interventions can even be viewed as experimental treatments, either implicitly (because different interventions are tried in different locations) or explicitly (e.g. by rolling out an intervention at different times to different locations), and therefore could be used to learn which interventions are most effective. To aid in the monitoring and evaluation of these treatments, several technological advances are making data collection user-friendly and nearly real-time. For example, Global Fishing Watch tracks and analyses global fishing activity using publicly available big data of AIS transmissions and images taken by satellites. In addition, traceability programs (both existing and emerging) aim to provide full traceability along the entire production chain. Such technical advances should be examined as a matter of priority and, if appropriate, deployed and utilised thoughtfully, so that these and other monitoring approaches help ensure that interventions are delivering their intended results.

10. Opportunities for Action

While it is clear that the appropriate capture fishery and mariculture reforms will be context-specific, several interventions seem to apply broadly across most situations. Here we briefly summarise those key opportunities for action to increase sustainable food from the sea.

GENERAL FOOD SYSTEMS
1. Consider food from the sea in the context of global food systems. Important linkages arise, including (1) inputs (wild fish are inputs to land-based food, and land-based plants are inputs to mariculture), and (2) substitution across land- and ocean-based protein sources.
2. The sustainable production of some food from the sea is associated with comparatively lower greenhouse gas emissions. Shifting diets towards these products may have important implications for climate change mitigation (Hoegh-Guldberg et al. 2019).
3. Recognise that food from the sea is particularly nutritious, as it contains omega-3 fatty acids and micronutrients essential for cognitive development and thus may play a particularly important role for children, pregnant women and nursing mothers. Consider how available resources (e.g. capture fisheries) can help address local nutritional deficiencies and need.

WILD FISHERIES
1. Conduct stock assessments of species of most importance for food, livelihoods and ecosystem health.
2. Implement management that controls harvest levels, preventing overfishing.
3. Move towards rights-based fishery management, including frameworks that provide a platform for co-management, cooperatives and local ownership and stewardship.
4. Implement climate-adaptive fisheries management via transboundary agreements and adaptive harvest control rules.
5. Remove capacity-enhancing subsidies, particularly in fisheries, that lack sound management.
6. Exploit and utilise low-trophic species judiciously. They are the base of the food web and can (1) increase the populations of higher-trophic species, (2) provide a highly nutritious and abundant food source for humans, and (3) promote continued mariculture growth for fed species.
7. In places that suffer from severe overfishing and low fishery governance, appropriately sized MPAs may help achieve fishery management goals and food provision.

MARICULTURE
1. Develop regulatory frameworks and revise existing regulations to address uncertainties and other barriers to sustainable mariculture expansion.
2. To recalibrate perceptions about mariculture, actively update agencies and consumers on state-of-the-art knowledge about sustainable mariculture practices.
3. Evaluate market failures and other impediments to technological innovations in mariculture feed, husbandry, farm design and so on. Consider policy interventions (such as taxes, subsidies, zoning and research) that would remove these barriers.

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Abbreviations

AIS	automatic identification system
B	biomass
B_{MSY}	biomass that enables the fish stock to produce MSY
bmt	billion metric tons
CAO	Central Arctic Ocean
CO_2	carbon dioxide
DHA	docosahexaenoic acid
DHC	direct human consumption
DNA	deoxyribonucleic acid
EPA	eicosapentaenoic acid
F	fish mortality
FAO	Food and Agriculture Organization of the United Nations
FIFO	fish in, fish out ratio
FM/FO	fishmeal/fish oil
F_{MSY}	maximum rate of fishing mortality that theoretically results in BMSY
GM	genetically modified
HAB	harmful algal bloom
IC	input control
IHC	indirect human consumption
IQ	individual quota
ITQ	individual transferable quota
IUU fishing	illegal, unreported and unregulated fishing
km	kilometre
m	metre
mmt	million metric tons
MPA	marine protected area
MR	marine reserve
MSY	maximum sustainable yield
mt	metric ton
PSMA	Port State Measure to Prevent, Deter and Eliminate Illegal, Unreported and Unregulated Fishing
R&D	research and development
RBFM	rights-based fishery management
RCP	Representative Concentration Pathway
RP	reference point
SAPEA	Science Advice for Policy by European Academies
SDG	Sustainable Development Goal
TAC	total allowable catch
TURF	territorial use right for fishing
US$/mt	United States dollar per metric ton

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About the Authors

Co-authors

Christopher Costello is a Professor of Environmental and Resource Economics at the Bren School of Environmental Science & Management at UC Santa Barbara and Director of the Environmental Market Solutions Lab (USA).

Ling Cao is an Associate Professor in the School of Oceanography at Shanghai Jiao Tong University (China).

Stefan Gelcich is an Associate Professor in the Ecology Department and the Center of Applied Ecology and Sustainability at Pontificia Universidad Católica de Chile.

Contributing Authors

Miguel Angel Cisneros is a Senior Researcher at the Instituto Nacional de Pesca y Acuacultura (Mexico).

Christopher M. Free is a Postdoctoral Researcher at UC Santa Barbara (USA).

Halley E. Froehlich is an Assistant Professor in the Department of Ecology, Evolution, & Marine Biology and Environmental Studies at UC Santa Barbara (USA).

Elsa Galarza is a Professor and Researcher of Economics of Natural Resources and Environment at the Research Center of Universidad del Pacífico (Perú).

Christopher D. Golden is an Assistant Professor of Nutrition and Planetary Health at Harvard T.H. Chan School of Public Health (USA).

Gakushi Ishimura is an Associate Professor at the United Graduate School of Agricultural Science at Iwate University (Japan).

Ilan Macadam-Somer is a Project Researcher at the Environmental Market Solutions Lab at UC Santa Barbara (USA).

Jason Maier is a PhD student at the Bren School of Environmental Science & Management at UC Santa Barbara (USA).

Tracey Mangin is a Project Researcher at the Environmental Market Solutions Lab at UC Santa Barbara (USA).

Michael C. Melnychuk is a Research Scientist at the University of Washington (USA).

Masanori Miyahara is President of the Fisheries Research and Education Agency of Japan.

Carryn de Moor is a Senior Research Officer at the Marine Resource Assessment and Management Group at the University of Cape Town (South Africa).

Rosamond Naylor is a Professor of Earth System Science and Founding Director of the Center on Food Security and the Environment at Stanford University (USA).

Linda Nøstbakken is a Professor at the Department of Economics at the Norwegian School of Economics (Norway).

Elena Ojea is a Senior Researcher at the Future Oceans Lab, CIM-Uvigo at the University of Vigo (Spain).

Erin O'Reilly is the Projects and Operations Coordinator at the Environmental Market Solutions Lab at UC Santa Barbara (USA).

Giacomo Chato Osio is the Water and Marine Resources Fisheries Officer at the European Commission Joint Research Centre (Italy).

Ana M. Parma is a Principal Scientist at the Center for the Study of Marine Systems at the National Scientific and Technical Research Council of Argentina.

Fabian Pina Amargos is a Professor of Protected Areas at the Center for Marine Research at the University of Havana, and an Environmental Advisor for Avalon-Marlin Diving, Snorkeling, and Fly Fishing Centers (Cuba).

Andrew J. Plantinga is a Professor of Natural Resource Economics and Policy at the Bren School of Environmental Science & Management at UC Santa Barbara and Lead Scientist in the Environmental Market Solutions Lab (USA).

Albert Tacon is the Technical Director at AquaHana LLC (USA).

Shakuntala H. Thilsted is the Research Program Leader for Value Chains and Nutrition at WorldFish (Malaysia).

HIGH LEVEL PANEL *for*
A SUSTAINABLE OCEAN ECONOMY

10 G Street NE
Suite 800
Washington, DC 20002, USA
+1 (202) 729-7600

oceanpanel.org