Estimating the Ocean's True Potential for Feeding the Planet
July 1, 2019

Project overview

The ocean currently plays an important role in global food security but neither capture fisheries nor ocean-based aquaculture are meeting their full production potential. It is estimated that 470 million metric tons (mmt) of protein will be required to feed the global population in 2050, which is projected to reach over 9.1 billion (FAO 2009). The growing population, along with increased urbanization and rising incomes, are expected to increase the demand for animal protein (FAO 2018). Furthermore, ocean protein can play a unique role in nutrition provision, as it contains omega-3 fatty acids and other essential vitamins and minerals (Kawarazuka & Bene 2010, Allison, Delaporte and Hellebrandt de Silva, 2013). The potential for seafood to contribute to future food security and nutrition has largely been absent from relevant policy discussions. The objective of this project is to quantify the ocean's true production potential to provide food though the development of supply curves that illustrate the potential production volume and associated costs of capture fisheries and ocean-based aquaculture. We developed four supply curves of total potential production (capture fisheries and aquaculture), representing different aquaculture feed scenarios, and present key findings disaggregated by sector. Impacts of climate change on capture fisheries and aquaculture production are not included in the scope of this study.

In this report, we summarize the methods, results, and key findings for the capture fisheries supply curve, aquaculture supply curve, and aggregate supply curve that combines both capture fisheries and aquaculture. A detailed methods section is included in Appendix A. Information regarding the underlying data (which is sent with the report) is included in Appendix B.

Capture fisheries supply curve

Summary of methods:
We modeled the production potential of over 4,500 fisheries across the globe, which represent 78% of current global landings, (see Appendix A for detailed methods) under two fishing effort scenarios: 1) F_{MSY} and 2) current F (F_0):

- F_{MSY} is the fishing mortality rate that results in maximum sustainable yield (MSY) when a stock's biomass is equal to B_{MSY}. MSY is the maximum catch that can be removed from the stock in perpetuity under constant environmental conditions. The constant application of F_{MSY} in a given fishery eventually results in B_{MSY} and maximum catch. The stock is considered to be in steady state when biomass and harvest remains constant over time.

- F_0 is the current fishing mortality rate (extracted from Costello et al. 2016). Its constant application in a given fishery will result in a steady state in which annual harvest is less than MSY.[1]

We found that the global maximum food production potential of capture fisheries[2] is 71.4 million metric tons (mmt).[3] However, this potential cannot be achieved under current fishing pressure. Steady state harvest under the F_0 scenario is 49.0 mmt, 32% lower than that of F_{MSY}, underscoring the important role that fishery management reforms will play in maximizing capture fishery production.

Importantly, because many fishers are motivated by profits, actual production will also be influenced by economic considerations. The fishing mortality rate that results in MSY is typically higher than that which results in maximized profits (thus, fisheries that maximize profits generally produce catch levels less than MSY). To better understand how economic factors including price and cost influence potential production, we determined the steady state production for each fishery under a range of prices (0-20,000 USD/mt), assuming that fisheries are managed to maximize future steady state profit. For each fishery, fishing effort scenario, and price combination, we calculated steady state profit by multiplying catch (which depends on the fishing effort scenario) by price and steady state cost by summing the cost of fishing and management. The cost of fishing scales with the fishing mortality rate, and therefore depends on the fishing effort scenario. The cost of management is based on the management assumption about the fishery and scales with harvest. Generally, better managed fisheries are assumed to be more costly to manage -- therefore, the cost of management is often greater under the F_{MSY} scenario compared to the alternative (F_0) (see Methods section for more information about costs). Then, for each price, we assumed that one of the following three fishing scenarios is adopted based on steady state profitability: 1) F_0, 2) F_{MSY}, 3) $F = 0$ (if neither F_0 or F_{MSY} are profitable at a given price, no fishing activity occurs and future production is equal to zero). Total production at each price was reduced to reflect the fact that 8% of harvest (called trimmings or by-products) is directed to the reduction industry to make fishmeal and fish oil, and that only a portion of the total remaining harvest is edible (Jackson and Newton 2016).

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[1] F_0 will result in a steady state harvest less than F_{MSY} unless $F_0 = F_{MSY}$.

[2] Global production values are calculated by scaling fishery outputs by 22% prior to aggregation in order to account for the portion of global landings that are not captured in the fishery database.

[3] It is estimated that 8% of catch volume (“trimmings” or “by-products”) is used for FM/FO reduction. To reflect the amount of catch potential available for human consumption, total harvest is scaled to account for this and then further converted into edible meat using conversion ratios based on Edwards et al. 2019.

Results and key findings

When considering economic factors, future food supply from capture fisheries has the potential to reach 69.7 mmt per year, which is 20.7 mmt (+42%) more than potential production at current fishing levels. This is slightly lower than the amount of food produced at the biological maximum (71.4 mmt), which assumes fishers maximize the amount of fish caught, regardless of profit maximization (this is less realistic, but could be possible with subsidies). Nearly 100% of this potential production (69.3 mmt) is attainable when price equals 3,500 USD/mt (Fig. 1). Under the current average global price for seafood landings (1,296 USD/mt; based on price information in Costello et al. 2016), 64.2 mmt would be produced.

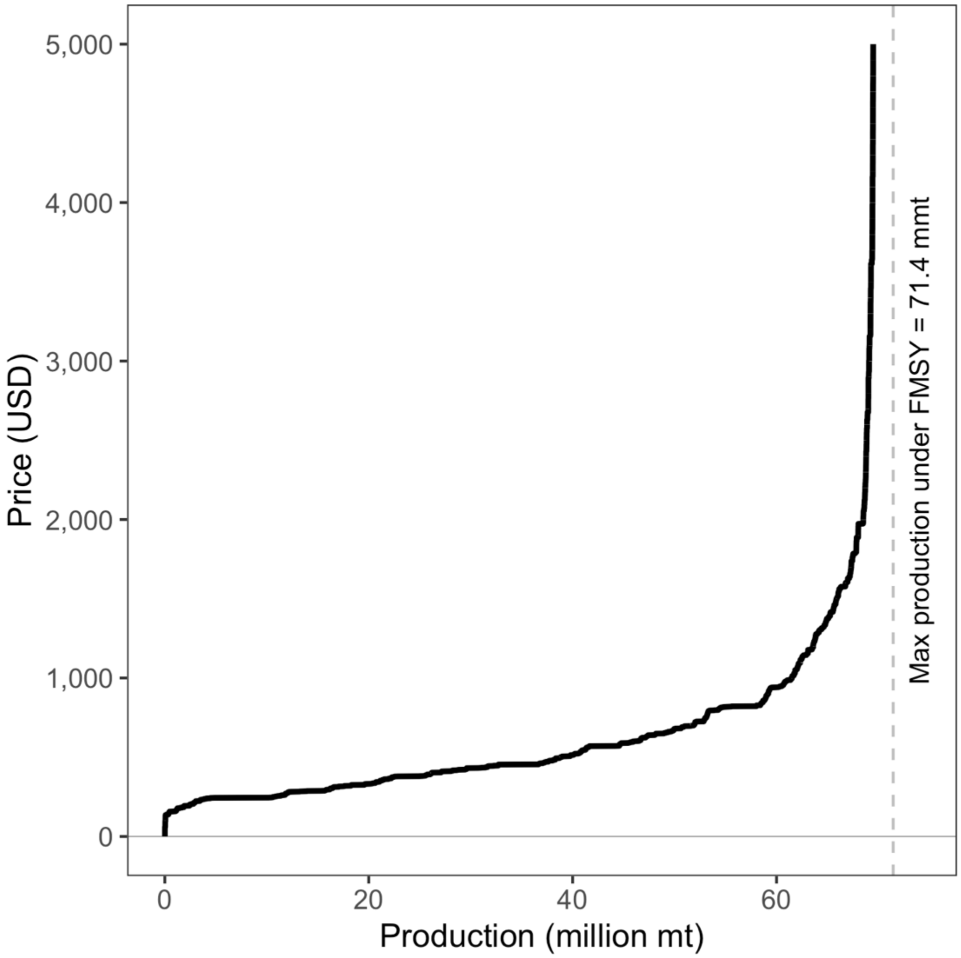

Figure 1. Total food production from capture fisheries in future steady state for prices ranging from 0 - 5,000 USD/mt. Total global production from all fisheries increases as the price increases.

As price increases, the number of fisheries that are most profitable under the F_{MSY} scenario increases. Half of the fisheries included in this study are most profitable under F_{MSY} under the current average seafood price. This value increases to 75% when price equals 2,000 USD.

Similarly, the percentage of total production that comes from reformed fisheries increases as price increases starting around 730 USD/mt. When price equals 3,500 USD/mt, 85% of total potential production is produced from reformed fisheries (Fig. 2).

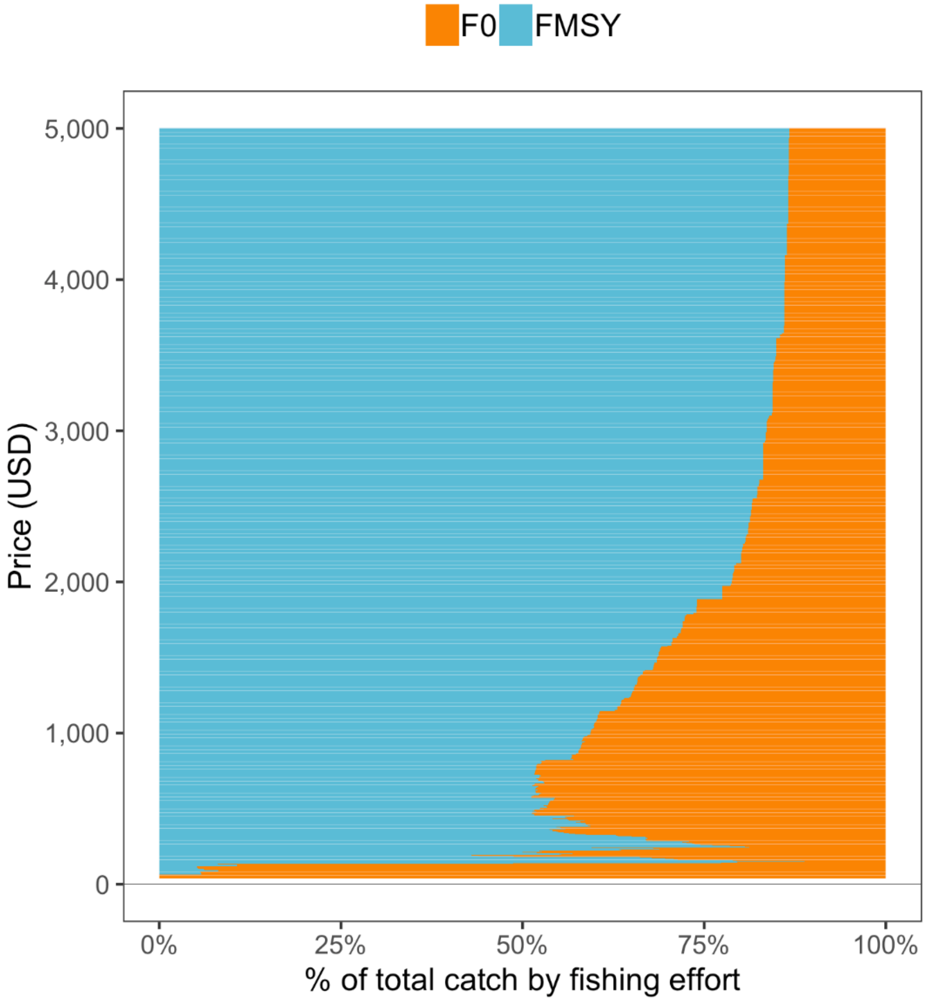

Figure 2. Total production from capture fisheries managed using F_0 (orange bars) and F_{MSY} (blue bars) for the price range 0-5,000 USD. Total global production and the number of fisheries managed by F_{MSY} increases as price increases. For prices below about 700 USD, the majority of production comes from a small number of large fisheries managed with F_{MSY} (it is unprofitable for most fisheries to operate at these prices, and thus the number of fisheries contributing to production is small).

The majority (80%) of future potential production comes from < 5% of fisheries, most of which adopt the F_{MSY} policy, suggesting that reform will play an important role in maximizing capture fishery production. This subset of fisheries has the potential to produce more food than all fisheries combined under sustained current fishing pressure (Fig. 3). The fisheries in this subset that adopt the F_{MSY} policy contribute an additional 16.0 mmt of annual production compared to their collective output under sustained current fishing effort (F_0). Of the fisheries that adopt the F_{MSY} policy, reforming fewer than a third of these fisheries results in over 90% of the additional production potential, and half of the production potential can be achieved by reforming just 12 fisheries (Appendix C).

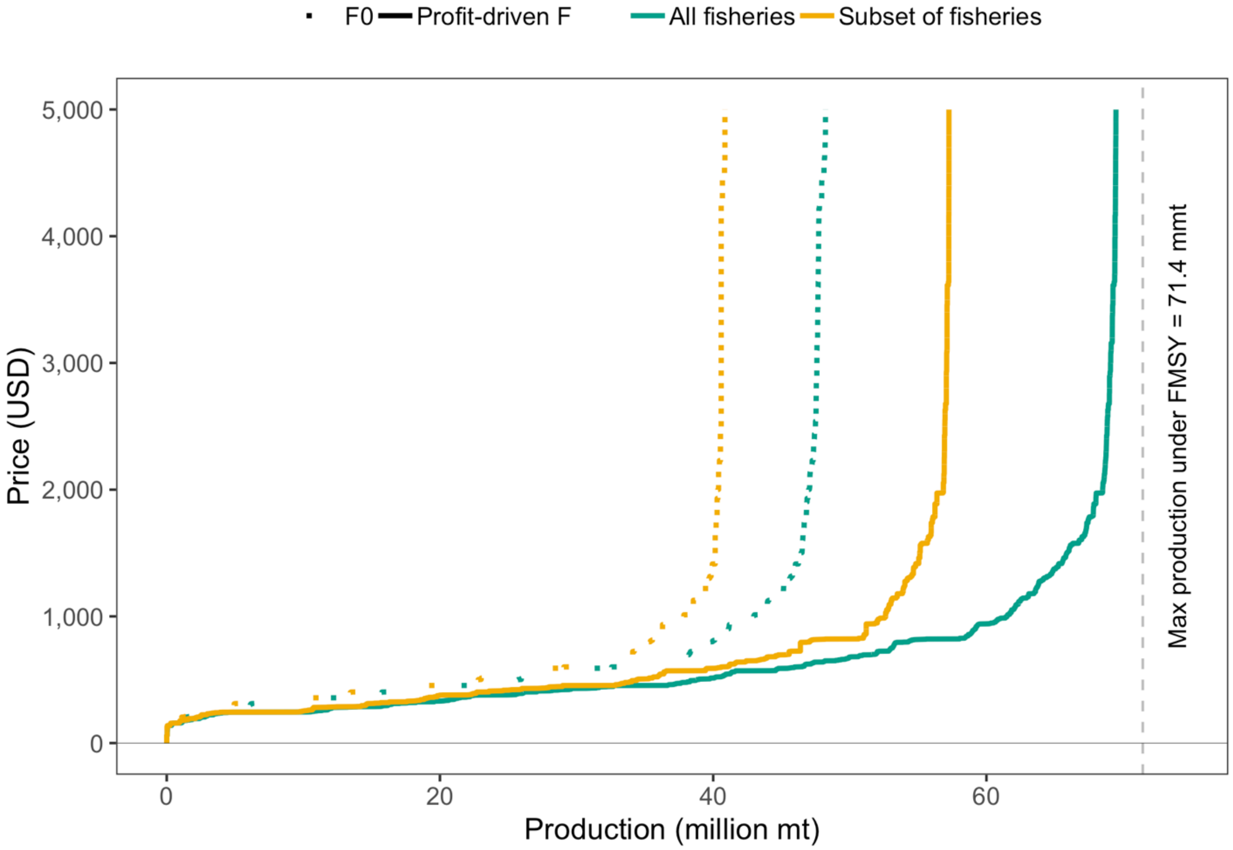

Figure 3. Total production potential for prices ranging between 0 and 5,000 USD for all capture fisheries (green) and the subset of fisheries (yellow) that produce 80% of future potential catch (< 5% of fisheries). The dotted line represents potential production under sustained current fishing pressure (F_0) (unprofitable fisheries do not add to potential production), while the solid line represents potential production when the management choice is profit-driven. The subset of fisheries, when managed based on potential profit, together have the potential to produce more catch than all of the fisheries combined if the F_{MSY} policy is not an option.

Potential additional production from reformed fisheries in subset are globally dispersed, with the largest potential increases in China, Chile, and the USA (Fig. 4). Other countries that have the potential for at least 1 mmt of additional harvest include Japan, Russia, Indonesia, Peru, and Argentina. In total, 122 nations have potential for additional production.

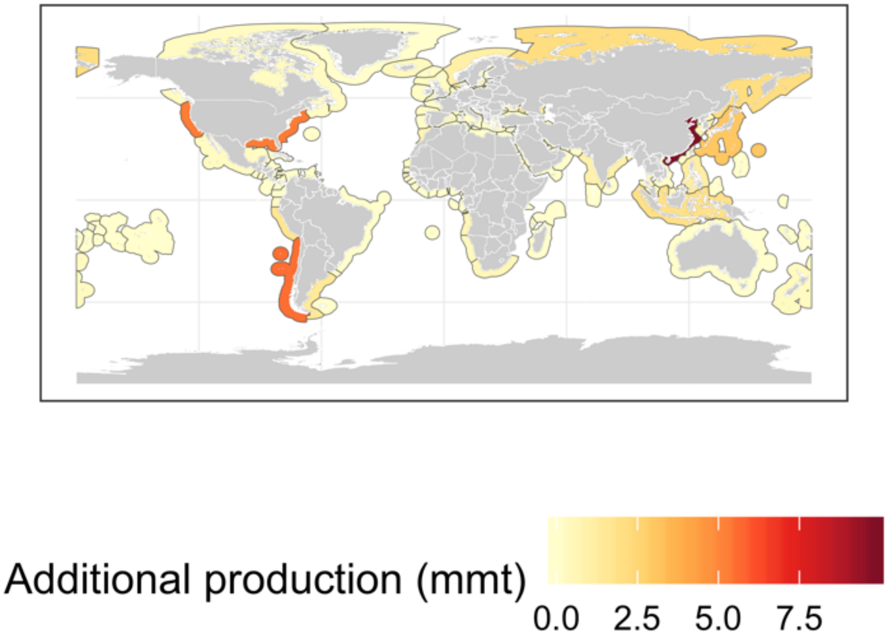

Figure 4. Additional production potential by exclusive economic zone (EEZ) for the subset of the < 5% of capture fisheries that would produce 80% of additional production potential and utilize the F_{MSY} policy.

Aquaculture supply curve

Summary of methods:

The true potential for ocean-based aquaculture (hereinafter referred to as aquaculture) can be estimated as the biological potential constrained by (1) ocean zoning conflicts; (2) financial feasibility; (3) fishmeal availability; and (4) other social and regulatory barriers. Here, we estimate the true potential for ocean aquaculture by accounting for constraints #1-2 and by evaluating four fishmeal availability scenarios (constraints #3). We do not account for social barriers such as public perceptions of aquaculture sustainability (Froehlich et al. 2017) or regulatory barriers such as precautionary aquaculture permitting (Krause et al. 2015, Knapp and Rubino 2016; constraint #4). However, the farm design employed in the production model employs best practices for aquaculture and thus represents sustainable design under best current knowledge.

We used the Gentry et al. (2017) estimates of global aquaculture potential as the biological potential for ocean finfish and bivalve aquaculture. Because Gentry et al. (2017) average rather than optimize the production potential of the 180 evaluated aquaculture species (120 finfish and 60 bivalve species), they likely underestimate the absolute maximum potential of aquaculture; thus, the results of this study present a conservative estimate of true aquaculture potential. Gentry et al. (2017) excluded areas allocated for other uses (i.e., marine protected areas, oil rigs, major shipping areas) as well as areas > 200 m deep (i.e., too expensive for development), thereby fully accounting for ocean zoning conflicts (constraint #1) and partially accounting for financial feasibility (constraint #2). We then estimated the cost of finfish and bivalve production as the sum of the amortized capital costs and annual operating costs and only considered profitable areas as being viable for ocean aquaculture (constraint #2). Next, we evaluated three scenarios in which the availability of fishmeal and fish oil (FM/FO) from capture fisheries further constrained finfish aquaculture production (constraint #3):

1. **Scenario 1:** FM/FO is only produced from the by-products of capture fisheries;
2. **Scenario 2:** FM/FO is produced from both the by-products of capture fisheries and landings from directed reduction fisheries; and
3. **Scenario 3:** FM/FO is produced from both by-products and reduction fisheries but the FM/FO demand of feed is reduced by 50%, 75%, or 95% (3 sub-scenarios) to reflect the potential for fish ingredients to be partially replaced by alternate ingredients in the near future.

In all three scenarios, the production of FM/FO from by-products and reduction fisheries reflects current consumer demand. We evaluated a fourth scenario in which finfish aquaculture production is unconstrained by fishmeal and fish oil availability. This scenario reflects the potential for fish ingredients to be entirely replaced by alternate ingredients in the future.

Results and key findings

Marine bivalve aquaculture is far under capacity and could produce 80.5 mmt of edible meat at current prices (Fig. 5). Although the maximum biological potential for bivalve aquaculture is 767.7 mmt per year, marine bivalve aquaculture currently produces only 15.3 mmt per year. This significant underage in capacity is likely due to prohibitive regulatory barriers in many countries of the world (Wardle 2017; Sea Grant 2019). For example, although aquaculture constitutes 47% of global fish production, the United States contributes less than 1% to this total (FAO 2018).

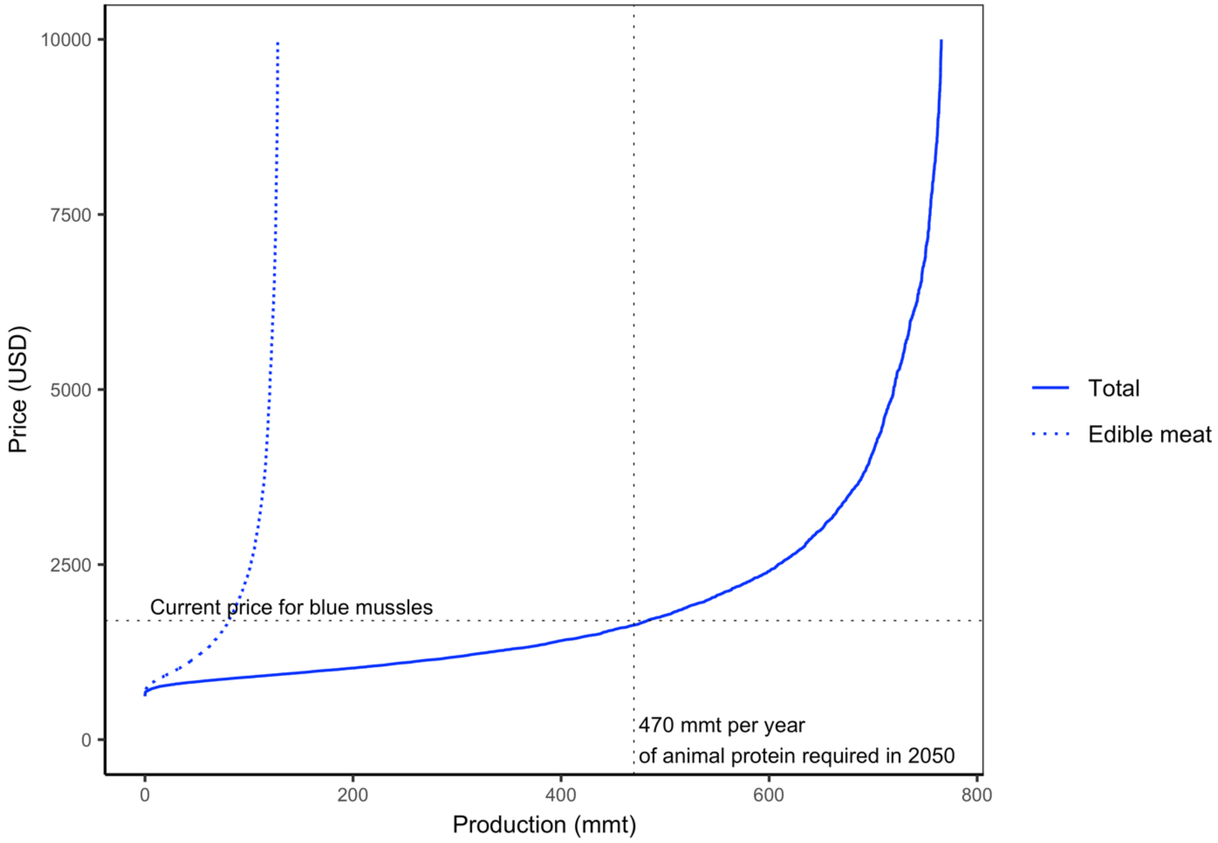

Figure 5. Bivalve aquaculture supply curve. With less stringent regulations, 80.5 mmt of production should be possible at the current price for blue mussels (US$1700 per mt; horizontal dashed line).

The potential for growth in finfish aquaculture is currently constrained by the availability of fishmeal and fish oil from capture fisheries (Figs. 6 & 7). Although the maximum biological potential for finfish aquaculture is 15.6 billion mt per year, a maximum of only 14.4 mmt per year of finfish production is feasible at present allocations of capture fisheries to reduction and optimal use of by-products from non-reduction fisheries (Scenario 2 – black lines; Fig. 6). A 50% reduction in the FM/FO requirements of feed would increase this potential to 28.8 mmt per year (Scenario 3 – thick blue lines; Fig. 6). This potential is constrained further when finfish aquaculture competes for space with bivalve aquaculture (Fig. 7).

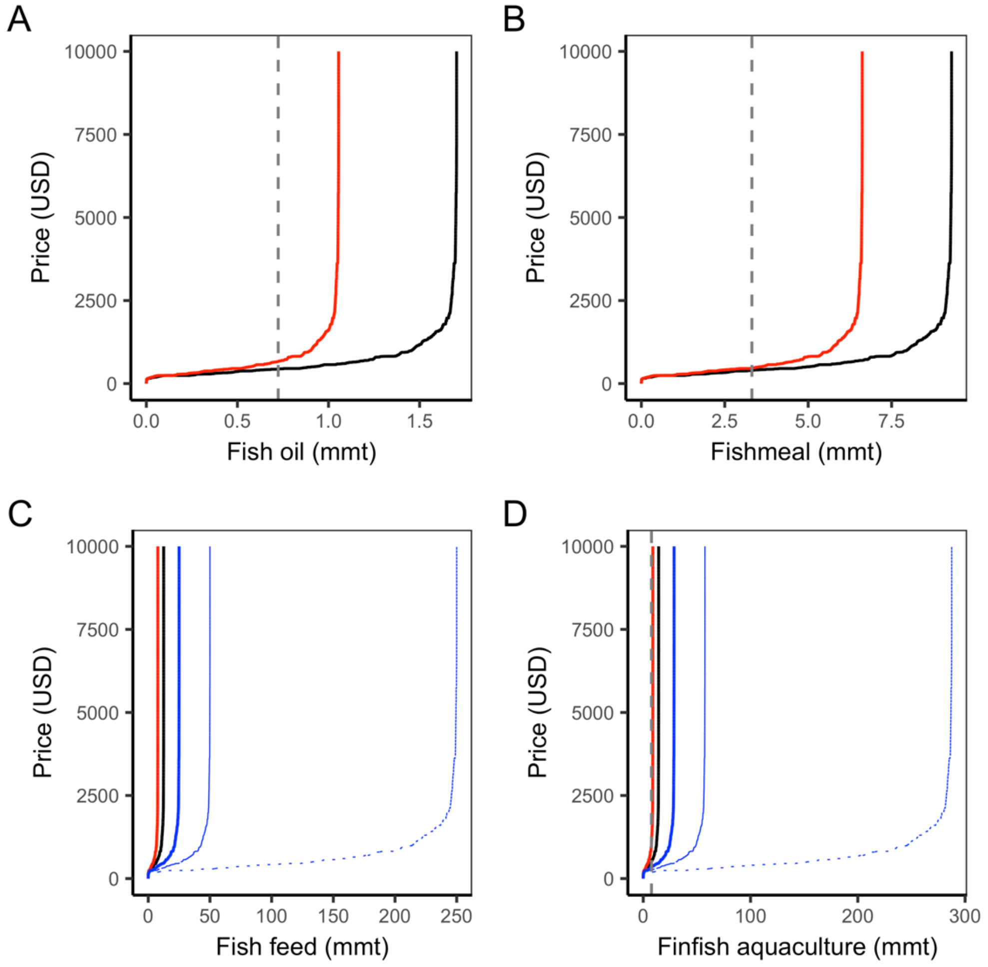

Figure 6. The availability of (A) fish oil and (B) fishmeal based on the price of seafood, (C) the amount of fish feed that can be derived from these ingredients (accounting for the proportion of fish oil and fishmeal diverted to uses besides fish feed), and (D) the amount of finfish that can be grown with this amount of feed for each of three scenarios: (1) FM/FO is produced from only the by-products of capture fisheries (red); (2) FM/FO is produced from both directed reduction fisheries and the by-products of non-reduction fisheries (black); and (3) Scenario 2 but with a 50% (thick blue), 75% (thin blue), or 90% (dotted blue) reduction in the amount of FM/FO required in feed due to technological advances. Vertical dashed lines indicate present day production.

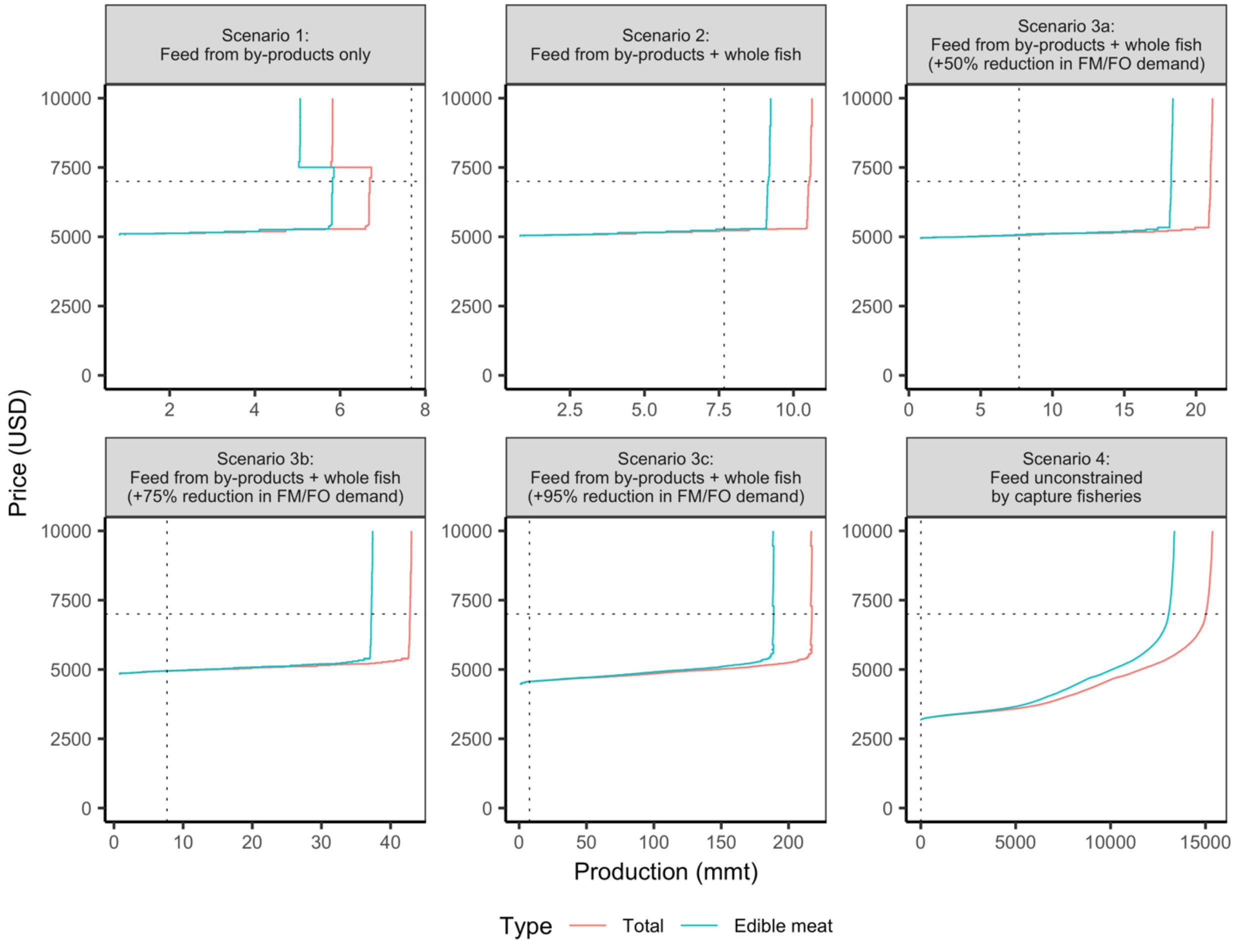

Figure 7. Finfish aquaculture supply curves. The horizontal dashed line shows the current price for Atlantic salmon (US$7000 per mt) and the vertical dashed line shows current marine finfish aquaculture production (7.7 mt). In Scenario 2, feed for finfish aquaculture is derived from both reduction fisheries and the by-products of non-reduction fisheries. In Scenario 3, feed for finfish aquaculture is derived from both reduction fisheries and the by-products of non-reduction fisheries with a (a) 50%, (b) 75%, and (c) 90% reduction in the FM/FO demands of feed due to technological advances). In Scenario 4, feed for finfish aquaculture is no longer constrained by capture fisheries due to the replacement of fish ingredients with alternative ingredients with technological advancements.

However, the potential for finfish aquaculture will increase as technological advancements reduce dependency on ingredients from capture fisheries production (Fig. 8). “Fish in, fish out” ratios are expected to continue to decline as fish ingredients are replaced with alternative sources of protein and starch and feed conversion ratios (FCRs) increase.

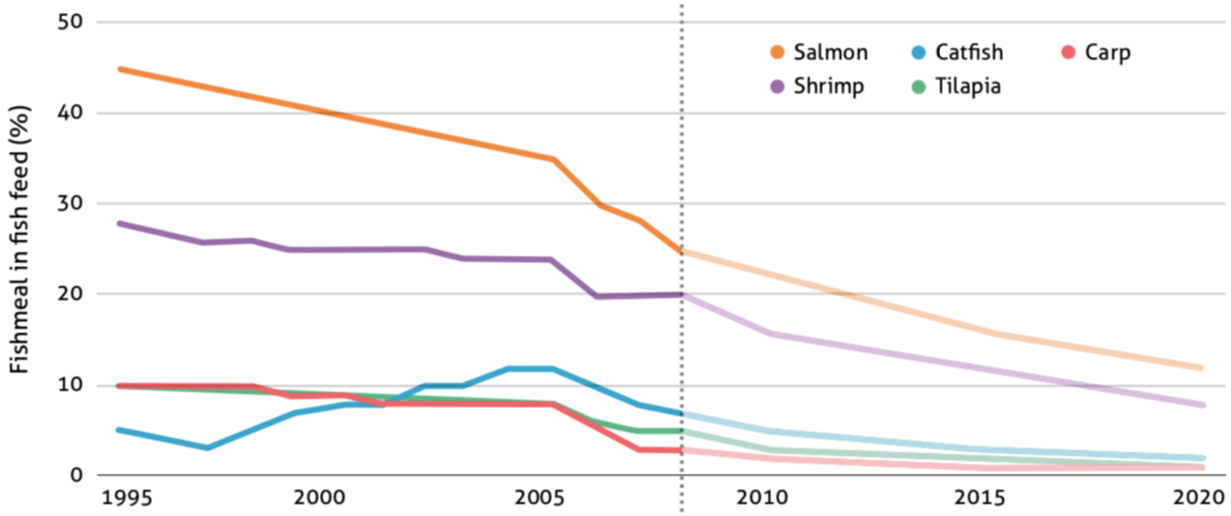

Figure 8. Historic (1996-2008) and projected (2009-2020) percentages of fish feed composed of fishmeal for five aquaculture species (from Porritt & McCarthy 2017 and adopted from Waite et al. 2014).

Aggregated capture fisheries and aquaculture supply curves

Summary of methods:

We aggregated the capture fisheries and aquaculture supply curves to generate overall ocean protein supply curves under four scenarios that constrain finfish aquaculture potential based on assumptions about the availability of fishmeal and fish oil (FM/FO) from capture fisheries:

- **Scenario 1: FM/FO is produced from only the by-products of capture fisheries**. 8% of capture landings are processed as by-products and directed to FM/FO production.
- **Scenario 2: FM/FO is produced from both the by-products of capture fisheries and whole fish from directed reduction fisheries.** 18% of capture landings are directly harvested for FM/FO production and 8% of the remaining landings are processed as by-products and directed to FM/FO production (24.6% of landings to FM/FO).
- **Scenario 3: 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%, 75%, or 95% (3 sub-scenarios).** This reflects the observed pattern where fish ingredients are being rapidly replaced by alternate ingredients in the near future. As in Scenario 2, 24.6% of capture landings are directed to FM/FO production.
- **Scenario 4: Finfish aquaculture 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 the future. In this scenario, all capture landings are available for human consumption.

Scenario 2 reflects present-day production of fish feed from capture fisheries while Scenarios 3 and 4 reflect production of fish feed that are likely for the near- to mid-term future given the pace of technological advancements in feed technology. Scenario 1 was evaluated to measure the food security tradeoffs involved in using capture landings for non-consumptive uses rather than for direct human consumption but is unlikely given both current and projected dietary preferences.

In all four scenarios, the finfish and bivalve aquaculture supply curves are aggregated into a single aquaculture supply curve assuming that finfish and bivalve aquaculture cannot occupy the same patch of ocean to be consistent with the best ecological practices for aquaculture. The most profitable aquaculture type is selected for each ocean patch at each price. This is a conservative assumption given that emerging integrated multi-trophic aquaculture (IMTA) approaches could reduce the environmental impacts of aquaculture while maintaining or even increasing production (Buck et al. 2018).

Results and key findings

The largest gains in the production of ocean protein will come from the development of marine aquaculture rather than capture fisheries. The ocean can only supply the 470 mmt of animal meat production required to feed 9.1 billion people by 2050 if prices are high and finfish aquaculture no longer requires fish ingredients in feed. However, high levels of protein production are possible with capture fisheries reform and development of bivalve aquaculture.

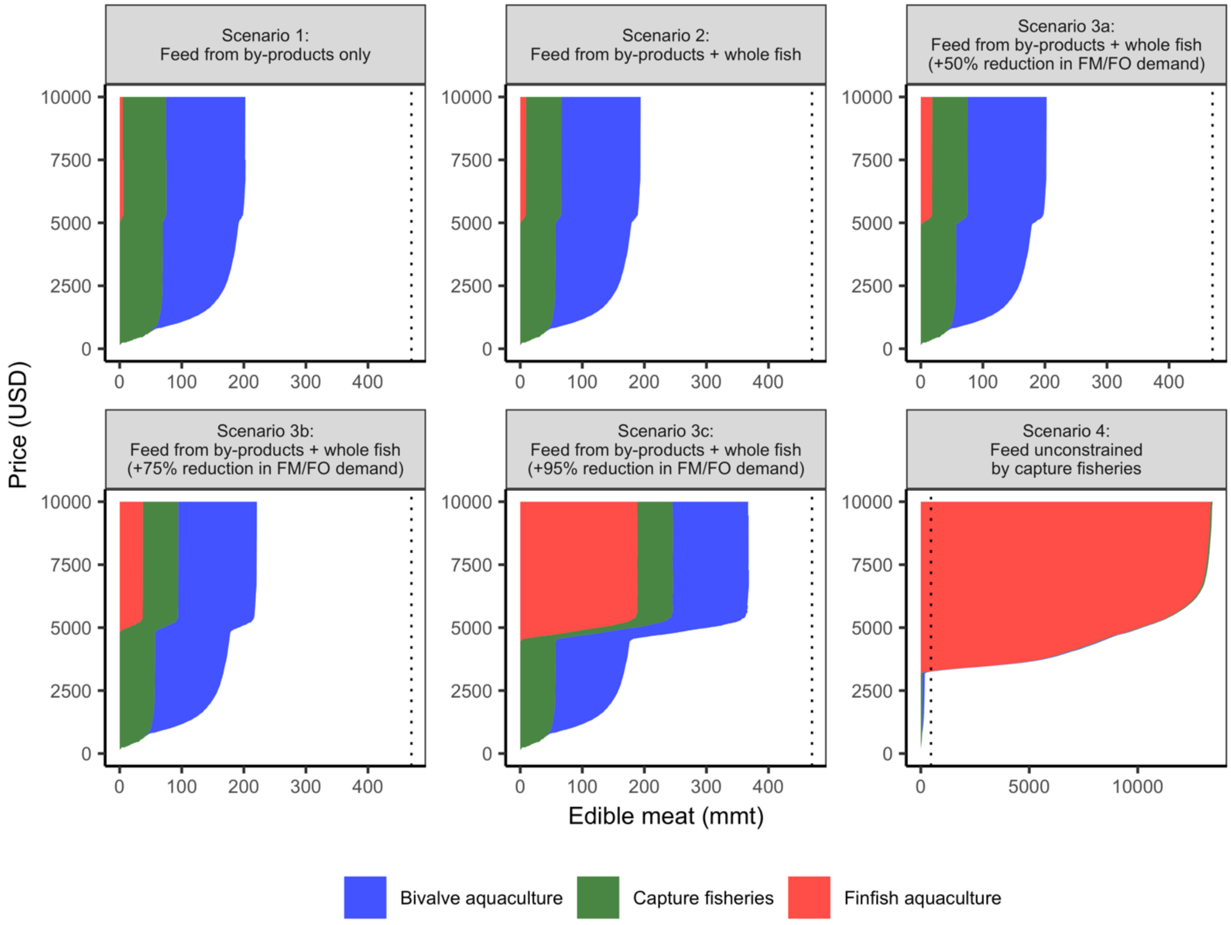

Figure 9. Combined supply curves for capture fisheries and marine aquaculture under four feed-constraint scenarios. In Scenario 1, feed for finfish aquaculture is derived from only the by-products of capture fisheries. In Scenario 2, feed for finfish aquaculture is derived from both reduction fisheries and the by-products of non-reduction fisheries. In Scenario 3, feed for finfish aquaculture is derived from both reduction fisheries and the by-products of non-reduction fisheries with a (a) 50%, (b) 75%, and (c) 90% reduction in the FM/FO demands of feed due to technological advances). In Scenario 4, feed for finfish aquaculture is no longer constrained by capture fisheries due to the replacement of fish ingredients with alternative ingredients with technological advancements. In all panels, the vertical dotted line shows the 470 mmt of animal meat production required to feed 9.1 billion people in 2050. Without feed constraints, the potential production from aquaculture exceeds projected global demands for animal protein at prices above $3251.

Appendix A: Detailed Methodology

1. Capture fisheries supply curve

Using a dataset of global fisheries developed by Costello et al., 2016, we modeled potential food production from 4,713 capture fisheries, which represent 78% of current global landings. The remaining 22% of fisheries not included in this dataset are likely small-scale, unassessed fisheries in relatively poor shape. We account for these fisheries by scaling fishery outputs in this study by 22%. Fishery-level parameters were borrowed from Costello et al. 2016. First, we calculated biological steady state (B/B_{MSY} in steady state) under two fishing effort scenarios: 1) F_{MSY} and 2) current F (F_0). Biological steady state is the level of biomass that would eventually occur under a constant fishing mortality rate. Biological steady state was calculated following the properties of the Pella-Tomlinson surplus production model:

$$f = \left(\frac{\phi+1}{\phi}\right)\left(1 - \frac{b^{\phi}}{\phi+1}\right) \qquad \text{Eq. 1}$$

Where ϕ is the Pella-Tomlinson shape parameter (extracted from Costello et al. 2016), f is the relative fishing mortality rate (F/F_{MSY}) (either F_{MSY} or F_0), and b is the biological steady state relative to (B/B_{MSY}).

Next, we calculated steady state harvest, H, as:

$$H = f * b * MSY \qquad \text{Eq. 2}$$

Where f is the relative fishing mortality rate, b is the biological steady state for a given f (calculated using equation 1) and MSY is maximum sustainable yield for that fishery (extracted from Costello et al., 2016).

We then calculated the total cost of producing steady state H. We included the extraction cost (or cost of fishing) and management costs as:

$$Total\ cost = c * (g * f)^{\beta} + H * managememt\ cost \qquad \text{Eq. 3}$$

Where c is a fishery-level cost parameter (extracted from Costello et al., 2016), g is a fishery-level growth parameter (extracted from Costello et al., 2016), f is the relative fishing mortality rate (determined by the scenario), β is a shape parameter (a $\beta > 1$ means that additional fishing effort is increasingly costly), H is steady state harvest determined by equation 2, and management cost is the cost of management per mt, which is based on a country-level database of management costs (Mangin et al 2018). Management cost values were assigned based on 1) the country in which the fishery exists and 2) the type of management applied (broadly open access, strong catch controls, or catch shares). Fisheries currently managed under catch shares or strong catch controls were assumed to have the same management cost under both fishing effort scenarios. Fisheries currently categorized as "broadly open-access" were assumed to have the broadly open-access value under F_0 and the strong catch controls value under F_{MSY}. Multinational fisheries were assigned average values for each of the three management types.

Finally, under a range of prices (0 - 20,000 USD/mt), we determined production from each fishery by choosing the fishing effort scenario that results in the greatest profit, defined by equation 4:

$$Profit = price * H - total\ cost \qquad \text{Eq. 4}$$

Where price is the price value (0-20,000 USD/mt), H is steady state harvest for scenario s (determined by equation 2), and total cost is the total cost for scenario s, defined by equation 3. When profit under both scenarios is less than zero, we assumed that fishing does not occur and 0 mt are produced for that fishery under that price. Otherwise, we assumed that the fishing scenario that results in the greatest profit occurs.

We make three adjustments to steady state harvests. First, we increased harvest for each fishery by 22% to account for the fisheries for which we had insufficient data to run a projection. Second, we reduced harvest values by 8% to account for the fact that some landed volume is directed to the reduction industry to make fishmeal and fish oil, and is thus not available for human consumption. Third, we reduce the remaining catch by 40% to account for the fact that typically only a portion of fish products are edible.

Fisheries that do not get reformed

There are some fisheries that do not get reformed, even when considering comparatively high prices. This occurs when the current fishing mortality scenario (fishing effort equals F_0 and management costs are associated with current management) results in greater profit in steady state compared to the reform scenario (fishing effort equals F_{MSY} and, for some fisheries, management cost increases with reform). There are three main reasons why this occurs:

1. Initial fishing mortality rate F_0 is close to the fishing mortality rate that results in maximum economic yield, or F_{MEY}. F_{MSY} results in maximum sustainable yield, but does not result in the greatest profit. Therefore, fisheries with current fishing mortality rates closer to F_{MEY} may experience greater profits from the F_0 scenario compared to switching to F_{MSY}.
2. The additional costs associated with improving management are greater than the economic benefit from management upgrades. This may occur in settings in which improved management is very expensive and/or the economic upside to reform is comparatively small.
3. The economic benefit from the fishery does not outweigh the cost of fishing.

2. Aquaculture supply curve

2.1 Overview

The true potential for ocean aquaculture can be estimated as the biological potential constrained by (1) ocean zoning conflicts; (2) financial feasibility; (3) feed availability; and (4) other social and regulatory barriers. Here, we estimate the true potential for ocean aquaculture by accounting for constraints #1-2 and by evaluating four feed availability scenarios (constraints #3). We do not account for social barriers such as public perceptions of aquaculture sustainability (Froehlich et al. 2017) or regulatory barriers such as precautionary aquaculture permitting (Krause et al. 2015, Knapp and Rubino 2016; constraint #4). However, the farm design employed in the production model employs NOAA best practices for aquaculture and thus represents sustainable design under best current knowledge.

We used the Gentry et al. (2017) estimates of global aquaculture potential as the biological potential for ocean finfish and bivalve aquaculture. Gentry et al. (2017) excluded areas allocated for other uses (i.e., marine protected areas, oil rigs, major shipping areas) as well as areas > 200 m deep (i.e., too expensive for development), thereby fully accounting for ocean zoning conflicts (constraint #1) and partially accounting for financial feasibility (constraint #2). We then estimated the cost of finfish and bivalve production as the sum of the amortized capital costs and annual operating costs and only considered profitable areas as being viable for ocean aquaculture (constraint #2). Next, we evaluated four scenarios in which the availability of fishmeal and fish oil (FM/FO) further constrains finfish aquaculture production (constraint #3):

- **Scenario 1:** FM/FO is produced from only the by-products of capture fisheries;
- **Scenario 2:** FM/FO is produced from both the by-products of capture fisheries and whole fish from directed reduction fisheries;
- **Scenario 3:** 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%, 75%, or 95% (3 sub-scenarios) to reflect the potential for fish ingredients to be replaced by alternate ingredients in the near future;
- **Scenario 4:** Finfish aquaculture production is unconstrained by the availability of fishmeal and fish oil from capture fisheries. This scenario reflects the potential for fish ingredients to be replaced entirely by alternate ingredients in the future.

In Scenarios 1-3, the production of FM/FO from by-products and directed reduction fisheries reflects current consumer demand.

2.2 Production potential

Gentry et al. (2017) used a three-step approach to estimate the global production potential for ocean finfish and bivalve aquaculture.

First, they calculated the *growth potential* for marine finfish (n=120) and bivalve (n=60) aquaculture species in each 0.042 degree patch of ocean. They mapped the areas where each species could be farmed based on its thermal tolerance then calculated the average growth performance index of the finfish and bivalve species that could be farmed in each ocean patch. The growth performance index, ϕ_i, is a unitless metric commonly used to describe and compare the growth rates of diverse species and is derived for species *i* as:

$$\phi_i = \log_{10} K_i + 2\log_{10} L_{\infty,i} \qquad \text{Eq. 5}$$

where $L_{\infty,i}$ is the asymptotic length and K_i is the growth coefficient from the von Bertalanffy growth equation for species i.

Second, they calculated the *production potential* for finfish and bivalve aquaculture by making straightforward assumptions about farm design (**Table 1**) and by estimating the time required to reach marketable size from the growth performance index. Each square kilometer of finfish farm was assumed to contain 24 x 9,000-m^3 cages stocked with 20 juveniles per m^3. Each square kilometer of bivalve farm was assumed to contain 100 x 4,000-m longlines seeded with 100 bivalves per foot. Marketable sizes for finfish and bivalves were assumed to be 35 cm (548 grams; "plate-size") and 4 cm, respectively. Gentry et al. (2017) estimated bivalve production in numbers of individuals and did not provide a weight for marketable bivalves. We calculated a market weight of 3.01 grams using allometry parameters (a=3.42; b=0.00001) for blue mussels from McKinney et al. (2004). Gentry et al. (2017) estimated the time required for finfish and bivalves to reach their marketable sizes in each ocean patch from the growth performance index of the patch using linear regressions fit to separate training datasets. Annual production potential (mt per yr), P_p, for patch p was then calculated as:

$$P_p = \frac{(N_{fish} * B_{market})}{T_{market,p}} * A_p \qquad \text{Eq. 6}$$

where N_{fish} is the number of fish or bivalves per 1 km^2 farm, B_{market} is the marketable weight of a fish or bivalve, $T_{market,p}$ is the number of years required to achieve marketable size in patch p, and A_p is the area of patch p.

Third, they constrained production potential based on a few environmental and human-use constraints. They excluded finfish areas with average growth performance indices below 2.0 or annual dissolved oxygen concentrations below the sub-lethal limit for finfish (4.41 mg l^{-1}). They excluded bivalve areas with average growth performance indices below 1.0, annual chlorophyll a concentrations below 2.0 mg m^{-3}, or more than two months per year with chlorophyll a concentrations below 1.0 mg m^{-3}. They also excluded areas in waters >200 m depth (i.e., too deep and expensive to anchor farms) and areas already allocated to marine protected areas, oil rigs, and high-density shipping lanes.

2.3 Production costs

The total annual cost (C_{total}) of aquaculture in each patch of ocean was calculated as the sum of the amortized capital costs ($C_{capital}$) and the annual operating costs associated with fuel (C_{fuel}), labor (C_{labor}), and other operational expenses ($C_{operations}$):

$$C_{total} = C_{capital} + \left(C_{fuel} + C_{labor} + C_{operations}\right) \qquad \text{Eq. 7}$$

where $C_{operations}$ includes expenses such as onshore workers, vessel and equipment maintenance, vessel dockage, insurance, and in the case of finfish, the cost of feed (C_{feed}) and the cost of stocking (C_{juvs}). The capital costs of both finfish (**Table 2**) and bivalve (**Table 3**) aquaculture include the purchase of vessels and equipment and the installation of this equipment. They were amortized using a 10% discount rate and a 10-year payoff period.

Annual fuel costs (C_{fuel}) were calculated assuming that each 1 km^2 farm requires 416 vessel trips per year (V_{trips}) and that vessels travel 12.9 km per hour (V_{speed}) and burn 60.6 liters of fuel per hour ($V_{efficiency}$). The price of fuel (F_{price}) was based on country-specific averages from the World Bank (2019a) and the trip distance (T_{dist}) was calculated for each patch as the minimum distance to shore. Thus, annual fuel cost for each patch of ocean was calculated as:

$$C_{fuel} = \sum_{i=1}^{\#\ of\ farms} \frac{(2 * T_{dist})}{V_{speed}} * V_{efficiency} * F_{price} * V_{trips} \qquad \text{Eq. 8}$$

where the number of farms per patch was determined by the area of the patch.

Annual labor costs (C_{labor}) were calculated assuming that each farm requires eight workers (W_{number}) working 2080 hours per year (H_{fixed}; 40 hours per week * 52 weeks) in addition to the hours required for round-trip transits ($H_{transit}$). Worker wages (W_{wages}) were based on country-specific averages from the World Bank (2019b). Round-trip transit time was calculated using the vessel speed and the number and distance of trips:

$$H_{transit} = \frac{(2 * T_{dist})}{V_{speed}} * V_{trips} \qquad \text{Eq. 9}$$

Annual feed costs (C_{feed}) for finfish aquaculture were determined by the annual production potential (AQ_{prod}) of each patch of ocean such that:

$$C_{feed} = \left(AQ_{prod} * FCR\right) * F_{price} \qquad \text{Eq. 10}$$

where annual feed demand was determined by the feed conversion ratio (FCR) and F_{price} is the cost of feed. Annual stocking costs (C_{juvs}) were calculated based on the farm specifications of Gentry et al. (2017) and these costs were amortized over the number of years required for juveniles to reach marketable size.

2.4 Feed constraint scenarios

2.4.1 Scenario overview

The potential for finfish aquaculture is constrained by the availability of feed required to nourish farmed fish. Fish feed is composed of a mixture of fishmeal, fish oil, vegetable oil, and alternative proteins and starch (e.g., soya beans, livestock by-products, cotton seeds, etc.). The fishmeal and fish oil (FM/FO) portions of feed are manufactured from either whole fish from fisheries that are fully or partially dedicated to feed production (i.e., reduction fisheries targeting forage fish) or by-products (a.k.a., trimmings or waste) from fisheries targeting fish for human consumption. Raw material from by-products – the processed offal (e.g., skeletons, guts, skin) from both wild and farmed fishes – is contributing to an increasing proportion of raw material available for FM/FO reduction. The rate at which feed is converted to fish is called the feed conversion ratio (FCR) and reflects the mass of feed required per mass of fish. For example, an FCR of 1.15 implies that 1.15 kg of feed is required to produce 1.00 kg of fish. Technological advances are lowering both FCRs and the proportional contribution of fish ingredients to feed. Together, these advances are increasing the mass of aquacultured fish that can be produced per mass of wild fish, a quantity known as the “Fish In, Fish Out” (FIFO) ratio.

We evaluated three scenarios in which FM/FO availability from capture fisheries constrains finfish aquaculture production:

- **Scenario 1:** FM/FO is produced from only the by-products of capture fisheries;
- **Scenario 2:** FM/FO is produced from both the by-products of capture fisheries and whole fish from directed reduction fisheries;
- **Scenario 3:** 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%, 75%, or 95% (3 sub-scenarios) to reflect the potential for fish ingredients to be replaced by alternate ingredients in the near future;

These scenarios assume the full potential (as opposed to the present day use) for by-products to generate FM/FO as identified by Jackson and Newton (2016). Otherwise, the scenarios are informed by the present day proportion of capture landings dedicated to FM/FO production (18% in 2010; Cashion 2017) and proportions of fishmeal and fish oil committed to marine aquaculture (73% and 80%, respectively; Shepherd and Jackson 2013). These scenarios are designed to capitalize on the full potential for by-products to support finfish aquaculture while accounting for human preferences for farmed fish versus other livestock fed fishmeal (pigs, chickens, other) and preferences for eating the forage fish that support reduction fisheries. Finally, we evaluated a fourth scenario in which finfish aquaculture production is unconstrained by fishmeal and fish oil availability. This scenario reflects the potential for fish ingredients to be entirely replaced by alternate ingredients in the future.

2.4.2 Scenario 1: Feed from by-products only

We used the analysis of Jackson and Newton (2016) to estimate the full potential for fishmeal and fish oil to be derived from the by-products of capture fisheries. Jackson and Newton (2016) used FAO, IFFO, and literature sources to estimate the amount of raw material, fishmeal, and fish oil currently derived from whole fish, by-products from capture fisheries, and by-products from aquaculture. They show that capture fisheries currently produce 3.7 million mt tons of raw material from by-products and that this raw material is converted to fishmeal and fish oil at rates of 26.4% and 4.2%, respectively. Together, this suggests that by-products from capture fisheries currently produce 993,000 and 158,000 mt of fishmeal and fish oil, respectively (**Table 5).**

However, the full potential for FM/FO production from by-products is larger than present-day values because not all landings are currently processed for by-products. Jackson and Newton (2016) estimate that 35.8 million mt of raw material could be generated from the by-products of capture and aquaculture fisheries combined. We estimated the capture fisheries portion of this potential to be 23.6 million mt given that 65.8% of by-product material currently comes from capture fisheries. Given a 27% and 4% conversion of raw material to fishmeal and fish oil, respectively, we further estimate that 9.5 and 1.5 million mt of fishmeal and fish oil could be produced from capture fisheries by-products, respectively. This implies that 6.9% and 1.1% of landings from capture fisheries become fishmeal and fish oil, respectively (**Table 5**).

From this, we calculated the availability of fishmeal (FM_p) and fish oil (FO_p) from the by-products of the wild capture fisheries production (WC_p) available at price p as:

$$FM_p = WC_p * 0.069 \quad \text{Eq. 11}$$

$$FO_p = WC_p * 0.011 \quad \text{Eq. 12}$$

where the proportions are the landings-to-ingredient conversion ratios derived above. However, fishmeal and fish oil are not only used for aquaculture. In 2010, 73% and 80% of fishmeal and fish oil went to aquaculture, respectively, with the remaining fishmeal going to livestock feed and remaining fish oil going to human consumption and industrial products (Shepherd and Jackson 2013). Thus, the fishmeal ($FM_{AQ,p}$) and fish oil ($FM_{AQ,p}$) available for aquaculture from the by-products of capture fisheries at price p is:

$$FM_{AQ,p} = FM_p * 0.73 \quad \text{Eq. 13}$$

$$FO_{AQ,p} = FO_p * 0.80 \quad \text{Eq. 14}$$

We determined how much fish feed ($Feed_p$) could be produced from these quantities assuming that fishmeal and fish oil constitutes 18.3% and 10.9% of fish feed, respectively (Ytrestøyl et al. 2015):

$$Feed_{FO,p} = \frac{FO_{AQ,p}}{0.109} \quad \text{Eq. 15}$$

$$Feed_{FM,p} = \frac{FM_{AQ,p}}{0.183} \quad \text{Eq. 16}$$

$$Feed_p = pmin\left(Feed_{FO,p}, Feed_{FM,p}\right) \quad \text{Eq. 17}$$

We determined how much finfish aquaculture (FAQ_p) this amount of feed could support using a feed conversion ratio of 1.15 for Atlantic salmon from Ytrestøyl et al. (2015):

$$FAQ_p = Feed_p * 1.15 \quad \text{Eq. 18}$$

2.4.3 Scenario 2: Feed from by-products and whole fish

The review of Cashion et al. (2017) indicates that approximately 18% of capture landings are directed to FM/FO production. Thus, we calculated the amount of landings available for FM/FO production from whole fish ($WC_{whole,p}$) at price p as:

$$WC_{whole,p} = WC_{p,i} * 0.18 \quad \text{Eq. 19}$$

where $WC_{p,i}$ is total capture landings at price p. Based on Jackson and Newton (2016), whole fish were converted to fishmeal and fish oil at rates of 22.4% and 4.85%, respectively:

$$FM_{whole,p} = WC_{whole,p} * 0.224 \qquad \text{Eq. 20}$$

$$FO_{whole,p} = WC_{whole,p} * 0.0485 \qquad \text{Eq. 21}$$

The production of fishmeal and fish oil from the by-products of the landings not directed as whole fish reduction inputs was then calculated as:

$$FM_{by,p} = (WC_p - WC_{whole,p}) * 0.069 \qquad \text{Eq. 22}$$

$$FO_{by,p} = (WC_p - WC_{whole,p}) * 0.011 \qquad \text{Eq. 23}$$

Total fishmeal and fish oil availability is thus the sum of the availabilities from whole fish and by-products such that:

$$FM_p = FM_{whole,p} + FM_{by,p} \qquad \text{Eq. 24}$$

$$FO_p = FO_{whole,p} + FO_{by,p} \qquad \text{Eq. 25}$$

The amount of finfish aquaculture that can be supported by these amounts of ingredients was calculated using the process described by Equations 9 through 14 above.

2.4.3 Scenario 3: Reductions in the FM/FO demand of feed due to technological advances

The amount of fishmeal and fish oil available from capture fisheries at each price *p* was calculated following the same assumptions and procedure used in Scenario 2 except that the FM/FO requirements of feed were reduced by 50%, 75%, or 95% (3 sub-scenarios) to reflect the potential for fish ingredients to be replaced by alternate ingredients in the near future.

2.4.4 Scenario 4: FM/FO availability is not limiting

In this scenario, aquaculture feed is assumed to be composed of entirely non-fish ingredients and finfish aquaculture is therefore unconstrained by capture fisheries production. The cost of feed is assumed to be the same as present day feed ($2.00 per kg).

2.5 Aggregating finfish and bivalve aquaculture supply curves

To be consistent with the best ecological practices for ocean aquaculture assumed by Gentry et al. (2017), we assumed that finfish and bivalve aquaculture cannot occupy the same patch of ocean. This is a conservative assumption given that emerging integrated multi-trophic aquaculture (IMTA) approaches could reduce the environmental impacts of aquaculture while maintaining or even increasing production (Buck et al. 2018). At each price *p*, we determined whether a patch of ocean would be used for finfish or bivalve aquaculture by assuming that the patch is used for the most profitable activity. Revenues, $R_{i,p}$, for patch i at price p were calculated as the profits minus the costs:

$$R_{i,p} = p * Prod_i - c_i * Prod_i \qquad \text{Eq. 26}$$

Where $Prod_i$ is the production potential of patch i and c_i is the cost of production in patch i. The cumulative feed demand of selected finfish aquaculture patches was tracked and additional finfish aquaculture could not occur once the feed available at price p was fully consumed.

2.5 Realism checks

We evaluated the realism of (1) our capture production to fishmeal and fish oil conversions and (2) our bivalve and finfish supply curves by confirming that present day production levels are possible at present day prices.

3. Ocean protein supply curve: aggregating the capture and aquaculture supply curves

We horizontally aggregated the capture and aquaculture supply curves to generate an overall ocean protein supply curve for each of the four scenarios. In Scenarios 1-3, this required subtracting the capture fisheries landings used for FM/FO production from capture fisheries.

In all scenarios, production of whole fish was converted to production of edible meat using the mean conversion ratios from Edwards et al. (2019) for finfish, crustaceans, and molluscs, and conversions based on these values for echinoderms and miscellaneous invertebrates. These values are 87% for finfish, 36% for crustaceans, 30% for echinoderms, 21% for miscellaneous invertebrates, and 17% for molluscs. We assume that horseshoe crab fisheries do not contribute to food production, as the fisheries in our database direct catch the biomedical sector. The value for miscellaneous invertebrates is based on the observed ratio in higher resolved groups (i.e., crustaceans and molluscs), and the value for echinoderms is the mean of the three original conversion values (i.e., crustaceans, molluscs, and fish).

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Table A1. Finfish and bivalve farm specifications from Gentry et al. (2017).

Parameter	**Value**
Finfish farm (1 km^2)	
Specifications	
Number of cages	24
Cage volume (m^3)	9,000
Stocking density (juvs m^{-3})	20
Marketable length (cm)	35
Marketable weight (g)	548
Derived quantities	
Total number stocked	4,320,000
Total biomass when harvested (mt)	2,367
Overall density when harvested (kg m^{-3})*	11.0
Bivalve farm (1 km^2)	
Specifications	
Number of longlines	100
Longline length (m)	4,000
Stocking density (juvs foot^{-1})	100
Marketable length (cm)	4
Marketable weight (g)[2]	3.01
Derived quantities	
Total number stocked	131,200,000
Total biomass when harvested (mt)	395
Overall density when harvested (kg m^{-1})[2]	9.9

* EU best practices maximum is 15 kg m^{-3}
Derived in present study

Table A2. Cost parameters for finfish aquaculture from Rubino 2008.

Type	Description	Unit	Baseline value	High-end value
Equipment costs				
capital	cage purchase	US$/m3	15	25
capital	cage mooring and installation[1]	US$/m3	3	3
annual	cage operating and maintenance[2]	US$/m3/year	1	6
Vessel costs				
annual	vessel fixed	US$/year	100,000	150,000
Feed costs				
annual	feed management variable	US$/cohort/month	0	33.32
annual	active feed monitoring variable	US$/cohort/month	0	33.32
capital	active feed monitoring fixed	US$/farm	0	10,000
annual	feed[3]	US$/kg	2.00	
Plans				
annual	insurance[4]	US$/year	50,000	300,000
annual	drug and chemical control BMP plan variable	US$/month	0	21.15
annual	solid control BMP plan variable	US$/month	0	21.15
capital	solid control BMP plan fixed	US$/farm	0	1615.2
capital	drug and chemical control BMP plan fixed	US$/farm	0	1615.2
Other costs				
annual	on shore cost[5]	US$/year	150,000	250,000

[1] Includes feeder and other equipment
[2] Includes fuel, utilities, diving, repair, etc.
[3] From Thomas et al. 2019
[4] Insurance covers fish and other capital
[5] Includes salaries for 1 manager and 2 office staff

Table A3. Cost parameters for bivalve aquaculture from Rubino 2008.

Type	Description	Units	Baseline value (used vessel)	High-end value (new vessel)
Equipment costs				
capital	longline equipment and installation[1]	US$/longline	10,000	
annual	expendable supplies[2]	US$/longline/year	1,700	
Vessel costs				
capital	vessel (+cost of upgrades to used vessels[3])	US$/vessel	95,000	800,000
annual	vessel maintenance	US$/vessel/year	10,000	30,000
annual	vessel equipment maintenance	US$/vessel/year	5,000	
Other costs				
annual	on shore cost[4]	US$/year	173,000	

[1] Includes 2 anchors ($2,000), 2 corner buoys ($2,000), rope and chain ($2,000), flotation ($2,000), and assembly and deployment ($2,000)
[2] Includes spat collectors, grow out ropes, socking material, bag, etc.
[3] Includes stripper/declumper/grader and continuous socking machine
[4] Includes CEO/captain salary ($100,000/year) and vessel dockage ($20,000/year), etc.

Table A4. Cost parameters common to both bivalve and finfish aquaculture.

Parameter	Value	Notes	Source
Labor costs			
Number of workers	8		Lester et al. 2018
Number of hours / yr	2080	40 hrs / week * 52 weeks = 2080 hrs (also paid for transit time)	Lester et al. 2018
Worker wage	by country	global average if not available	World Bank 2019b
Fuel costs			
Vessel trips per year	416	1 vessel makes 5 trips/wk, 1 vessel makes 3 trips/wk	Lester et al. 2018
Vessel speed (km/hr)	12.9	8 miles per hour	Lester et al. 2018
Vessel fuel efficiency (liters/hr)	60.6	16 gallons per hour	Lester et al. 2018
Fuel cost (USD/liter)	by country	global average if not available	World Bank 2019a
Trip distance (km)	based on farm location		

Table A5. Deriving the percentage of landings from capture fisheries converted to FM/FO production when by-products are fully collected and processed as described by Jackson and Newton (2016).

Value	WC and AQ by-products	WC by-products only	Source
FM/FO production potential			
Raw material (millions mt)	35.8	23.6*	WC value derived assuming that 65.8% of by-product material comes from WC fisheries
Fish oil (millions mt)	1.5	1.0*	WC value derived assuming that 4% of raw material becomes fish oil
Fish meal (millions mt)	9.5	6.3*	WC value derived assuming that 27% of raw material becomes fish meal
FM/FO as a percentage of seafood production			
Production (millions mt)	160.7	90.6	Both values from FAO (2018) for 2013
% of production to fish oil	0.9%*	1.1%*	Derived as fish oil production divided by overall production
% of production to fish meal	5.9%*	6.9%*	Derived as fish meal production divided by overall production

* Values marked with asterisks were derived using the quantities (the values without asterisks) reported by Jackson and Newton (2016).

Table A6. Relevant finfish aquaculture, feed, fishmeal, and fish oil parameters and production statistics.

Parameter	Value	Source	Notes
Feed composition statistics			
Feed conversion ratio (FCR)	1.15	Ytrestøyl et al. 2015	Atlantic salmon in Norway
% of feed that is fish oil	10.9%	Ytrestøyl et al. 2015	Atlantic salmon in Norway
% of feed that is fishmeal	18.3%	Ytrestøyl et al. 2015	Atlantic salmon in Norway
% of feed that is fishmeal/fish oil	29.2%	Ytrestøyl et al. 2015	Atlantic salmon in Norway
FM/FO production statistics			
2016 fish oil production (mt)	904,900	IFFO 2017	
2016 fish meal production (mt)	4,538,800	IFFO 2017	
% of fish oil production to aquaculture	80%	Shepherd and Jackson 2013	
% of fishmeal production to aquaculture	73%	Shepherd and Jackson 2013	
Aquaculture production statistics			
Price for blue mussels (US$ / mt)	1700	BIM 2017	
Price for Atlantic salmon (US$ / mt)	7000	EY 2018	
2016 marine finfish aquaculture production (mt)	7,672,412	FAO 2018	
marine salmon aquaculture production (mt)	2,618,999	FAO 2018	
2016 marine bivalve aquaculture production (mt)	15,335,641	FAO 2018	
marine mussel aquaculture production (mt)	2,007,507	FAO 2018	
% of blue mussel mass yielding edible meat	24%	FAO 1989	

Appendix B: Description of data files.

Capture fisheries supply curve data
This file contains the outputs for the capture fishery supply curve. This information can be disaggregated spatially (e.g., by country, FAO region) and by species type. This file contains the outputs for the capture fishery supply curve. This information can be disaggregated spatially (e.g., by country, FAO region) and by species type. There are two production outputs included in this file: harvest (harvest_mt) and edible production (meat_mt). The values in the report represent edible production. Metadata for the data is as follows:

Filename: capture_supply_curve.rds

Column name	**Units**
id_orig	Identification
comm_name	Common name
sci_name	Scientific name
species_cat	International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) code
species_cat_name	ISSCAAP group of species name
country	Country name
RegionFAO	FAO region(s)
price	Price (USD)
f_policy	F_{MSY}, F current (F_0), no fishing
harvest_mt	mt
meat_mt	mt

Ocean supply curve data

This file contains the outputs from the aggregated capture fisheries, bivalve aquaculture, and finfish aquaculture curves for each of the four scenarios. A total supply curve can be constructed by summing the production of sectors at each price.

Filename: ocean_supply_curve_scenarios1-4.csv

Column name	**Units**
scenario	Scenarios 1-4
sector	Capture fisheries, finfish aquaculture, or bivalve aquaculture
price	1-20,000 USD per metric ton (mt)
mt_yr	Metric tons (mt) of whole organism production per year
meat_yr	Metric tons (mt) of edible meat production per year

Appendix C: Top twelve fisheries in terms of additional harvest potential.

Stock name	**Scientific name**	**Country**	**B/B_{MSY}**	**F/F_{MSY}**	**MSY (mt)**	**FAO Area**
Horse Mackerel Chile	*Trachurus trachurus*	Multinational	0.088	1.71	3476694	87
Largehead hairtail	*Trichiurus lepturus*	China	2.209	0.143	3465641.67	61
Chilean jack mackerel Chilean EEZ and offshore	*Trachurus murphyi*	Multinational	0.024	5.75	1281278.69	87
Threadfin breams nei	*Nemipterus* spp.	China	0.822	0.341	1186467.6	61
Cunene Horse Mackerel West Africa	*Trachurus trecae*	Multinational	0.186	2.62	719170.875	34,47
Blue Whiting Northeast Atlantic	*Micromesistius poutassou*	Multinational	0.689	0.239	717870.715	27
Jack and horse mackerels nei	*Trachurus* spp.	Multinational	0.154	2.316	680781.676	34
Sandeel North Sea Area 1	*Ammodytes marinus*	Multinational	2.5	0.166	633650.762	27
South American pilchard	*Sardinops sagax*	Peru	0.537	0	501320.459	87
Atlantic cod North Sea	*Gadus morhua*	Multinational	0.046	3.56	383694.406	27
South American pilchard	*Sardinops sagax*	Chile	0.458	0.001	373027.355	87
Chub mackerel	*Scomber japonicus*	Multinational	0.3	6.83	344497.398	61