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Supplementary information

The future of food from the sea

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The Future of Food from the Sea: Supplementary Information

Costello et al.

1 Supplementary methods

1.1 Historical Seafood Production

We calculated historical food production using the FAO's global fisheries landings statistics and aquaculture production statistics, both accessed through FishStatJ[1]. We removed landings and aquaculture production that were classified as primarily directed towards non-food uses, such as horseshoe crabs (which are used for biomedical purposes), natural sponges, and landings used for ornamental purposes. We also removed landings of turtles, whales, tunicates, seals, platonic crustaceans and aquatic plants. Although aquatic plants contribute to food supply, we do not report this source since we do not model future production from the sector. This resulted in estimates of landings from capture fisheries and production from aquaculture that contribute to food production. Additional details are provided below for marine wild capture fisheries (section 1.1.1), fed and unfed mariculture (section 1.1.2), and inland fisheries and aquaculture (section 1.1.3). We applied adjustments for the proportion of catch directed towards reduction fisheries and for the proportion of catch that is edible (see section 1.1.5).

This section describes the methods for calculating several baseline values used for analyses. These values are used as initial production values throughout the text, to calculate percentages relevant to current production, and to create demand curves for each sector. The focus of our analysis is on marine fisheries and mariculture. We discuss our treatment of inland fisheries and inland aquaculture production separately from marine production. Section 1.5 discusses how these sectors are related and provides analyses to explore the implications of substitution between inland and marine aquatic foods.

1.1.1 Current marine capture (i.e. wild) fisheries food production

In our study, we use fishery-level data from Costello et al. (2016) to project future food production from marine capture fisheries under different management scenarios. To remain consistent with our projections and wild fisheries supply curve, we calculated current food production from wild fisheries using the most current (2012) catch data from Costello et al. (2016)[2]. To calculate initial food production with these data, we filtered the fishery-level database for the year 2012 and removed 11 stocks that lacked adequate data for projections. The sum of 2012 harvests for the 4,702 fisheries included in our study represents 79% of total 2012 landings as reported to the FAO (main text Fig. 1). We scaled harvest from each fishery up by 27% in order to account for small fisheries that are not included in this database and to match FAO outputs.

1.1.2 Current finfish and bivalve mariculture food production

To calculate current food production for finfish and bivalve mariculture (the two mariculture sectors included in our study), we used 2017 production quantities from FAO's production statistics[1]. We summed the production quantities for finfish fisheries and converted this value to edible food quantity using the conversions described in Section 1.1.5. Current bivalve production is simply the production of molluscs converted into edible food. In our study, finfish production requires feed inputs while bivalve production does not and is considered an "unfed" sector. We used the resulting values as initial conditions to construct our supply and demand curves. We excluded the production of seaweed and fisheries classified as something other than finfish and molluscs in our baseline calculations because we only model these two sectors in our analysis. Note that the total current food production from mariculture was calculated by summing estimated food production for all mariculture of aquatic animals in 2017 using FAO production data (main text Fig. 1). Because this includes additional species groups (e.g., crustaceans), this number differs from that presented in main text Fig. 5 under "Initial production". Mariculture production represents 19% of current food from the sea, while finfish and bivalve mariculture production together account for 16% of current food from the sea (main text Fig. 5).

1.1.3 Current inland food production

Although our main analysis is focused on food from the sea, we do integrate estimates of food from inland fisheries in various ways. To calculate current food production from inland capture fisheries and inland aquaculture, we used 2017 production values from FAO statistics[1] (see section 1.1). We did this for inland capture fisheries and inland aquaculture production together as an aggregate sector of inland aquatic food production. We also considered inland capture and inland aquaculture production separately to generate inland aquatic food supply curves, described in section 1.4.

1.1.4 Current meat production

We used 2017 production quantities from the FAOSTAT food production data for bovine meat, mutton and goat, pigmeat, poultry meat, edible offals, and "other livestock" to calculate non-seafood meat production (Table S1). We convert these values from carcass weight to edible meat using conversion rates in Nijdam et al. (2012)[3] (Table S2). We apply the mean of pigmeat, poultry meat, mutton and goat, and bovine meat conversion values to edible offals and "other livestock." This results in 250 mmt of non-seafood meat production. We then add current food production from inland fisheries (50.7 mmt), marine capture fisheries (49.4 mmt, see above section 1.1.1 for details regarding calculation), and total mariculture production in 2017 (11.6 mmt), resulting in a total of 362 mmt of edible meat production.

Meat Group	Prod. (mmt)	Food (mmt)
Poultry	111.8	89.5
Pork	115.7	86.8
Beef	66.3	46.4
Edible offal	16.7	12.5
Mutton & Goat	13.7	10.3
Other livestock	6.2	4.6
Inland capture	11.9	9.8
Inland aquaculture	49.0	40.8
Marine capture	77.4	49.4
Mariculture	30.6	11.6

Table S1: Initial global production of animal meat. Production quantity represents carcass-weight for livestock (i.e., poultry, pork, beef, edible offal, mutton goat, and other livestock meat), and live-weight for aquatic animals (i.e., inland capture, inland aquaculture, marine capture, and mariculture). Production quantity is converted to edible food quantity using conversions from Nijdam et al. (2012) and Edwards et al. (2019). All production data are from FAOSTAT[4], except for marine capture, which is from Costello et al. (2016).[2]

Meat Group	Conversion Factor
Poultry	0.80
Pork	0.75
Beef	0.70
Edible offal	0.75
Mutton & Goat	0.75
Other livestock	0.75

Table S2: Conversion factors used to convert livestock carcass-weight to edible quantities. Conversion factors for poultry, pork, beef, mutton goat are from Nijdam et al. (2012)[3]. We apply the mean conversion rate for these sectors to edible offal and other livestock meat.

1.1.5 Converting landings and aquaculture production to edible quantities

We applied two conversion factors to calculate the total food available from capture fisheries and aquaculture. First, to account for the share of marine wild landings directed to the reduction industry for fishmeal and fish oil production (18% in 2010[5]), we applied an 18% reduction in total harvest for each marine fishery. In reality, specific fisheries (generally forage fish species such as Peruvian anchoveta) are targeted for the reduction industry. We used a single value for all fisheries because we were unable to reproduce the 18% value reported by Cashion et al. (2017) using the fishery-level (country-species couple) proportions reported by Cashion (2016)[5,6], but because we ultimately aggregate all wild marine fisheries together, this discrepancy is minor.

Second, we converted whole fish production 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[7]. These values are reported in Table S3. Again, we assumed that horseshoe crab fisheries do not contribute to food production, as landings from the horseshoe fisheries in our database are directed to 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).

After applying these two adjustments, we compared the converted quantities for marine wild capture fisheries to FAO food production data accessed through FishStatJ[1]. We noted a small discrepancy of about 1 mmt for data in 2012, but this does not qualitatively affect our results.

Fish Group	Conversion Factor
fish	0.87
molluscs	0.17
crustaceans	0.36
echinoderms	0.30
miscellaneous invertebrates	0.21

Table S3: Seafood conversion factors used to convert live-weight to edible quantities for aquatic animals. Conversion factors for fish, molluscs, and crustaceans are from Edwards et al. (2019)[7]. We estimated conversion factors for echinoderms and miscellaneous invertebrates based on these conversion factors (see section 1.1.5 for details)

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1.1.6 Projected future meat "needs”

While our approach projects future shifts in demand *curves*, other authors often report estimates of the future *quantity* of meat demanded, often expressed on a per-capita basis. To compare our results against this approach, we need to establish a reasonable benchmark for 2050 using both livestock and fish estimates. Livestock need was projected in FAO's World Agriculture Towards 2030/2050 report, which predicted that in 2050, 49.4 kg of meat per capita would be required for consumption[8]. This number is reported in carcass weight, so we then converted carcass weight to edible weight using two factors. First, since livestock animals have different carcass-to-edible meat conversions, we broke down the 49.4 kg of meat into the four livestock sectors (beef, mutton, pigmeat, and poultry) using the fraction of production for that sector in 2050 to total meat production in 2050. Those numbers were then converted to edible meat using conversions from Nijdam et al. (2012)[3], available in Table S2. A total of 37.46 kg/capita of edible meat from livestock was calculated for 2050.

Because fish were excluded from the projections in the World Agriculture Towards 2030/2050 report, to be consistent, we require an estimate of the need for fish per capita. As a reference, we used 2007 edible production values from main text Fig. 1, which uses data from FAOSTAT and conversion factors from Edwards et al. (2019)[7], and divided by the world population in 2007 to result in 13.73 kg/capita edible fish consumption. For edible fish need in 2050, we then multiplied kg/capita consumption by the same growth rate as predicted for meat production listed in the World Agriculture Towards 2030/2050 report, yielding 17.52 kg/capita of edible fish[8].

The sum of these numbers provides an estimate of the quantity of meat demanded in 2050 of 54.98 kg/capita. Multiplying by the estimated world population in 2050 (9.8 billion), and converting to mmt provides an estimate of 539 mmt. We use this calculated benchmark as a means for comparison with the numbers we derive from supply and demand curves and we also compare it in the text to our estimate of current meat consumption (362 mmt).

1.1.7 Current global prices

- *Wild marine capture fisheries*: We calculated the average global price for wild fishery food production using Costello et al. (2016)'s global fishery database[2] and Melnychuk et al. (2016)'s global price database[9]. The price for Peruvian anchoveta (*Engraulis ringens*) was updated to USD 250 per mt based on personal communications with regional fishery experts. We calculated the mean global price for the most recent year in the database (2012), weighting by food production (catch coverted to food). This results in a weighted mean of USD 1,154 per mt.

- *Finfish mariculture*: We used the current ex-farm price for Atlantic salmon (USD 6,193 per mt), milkfish (USD 1,545 per mt[4]), and barramundi (USD 4,384 per mt[4]) to calculate a mean global price for finfish mariculture, weighted by food production. Production of these three species groups represents 55% of all finfish mariculture in 2017. To calculate the mean global price, we filter 2017 production for salmon, milkfish, and barramundi production in 2017 and convert harvest to food. Then, using the ex-farm prices, we calculate the mean price weighted by food, to obtain a weighted mean price of USD 4,408 per mt of food. We use parameters for Atlantic salmon in the analysis that appears in the main text. In addition, we run sensitivity analyses using parameters for milkfish and barramundi.

- *Bivalve mariculture*: We used the current ex-farm price for blue mussels (USD 1,700)[10].

- *Inland fisheries*: We calculate the average global price for inland capture fisheries as the quantity-weighted mean price for the four inland fisheries product categories. We used the current ex-farm price for carp (USD 2,847 per mt[11]), the current ex-farm price of tilapia in China, the global leader in farmed tilapia production (USD 1,584[12]), the ex-farm price of catfish in Vietnam, the global leader in catfish aquaculture production

(USD 2,589[13]), and the average price of inland-produced aquatic foods for the aggregate *other* category (USD 2,174[14]).

1.2 Marine Capture Fisheries Supply Curve

We calculated biological steady state ($\frac{B}{B_{MSY}}$ in steady state) under two fishing effort scenarios: (1) yield-maximizing fishing mortality ($F = F_{MSY}$) and (2) current fishing mortality ($F = F_0$). 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:

$$f = \frac{\varphi + 1}{\varphi}\left(1 - \frac{b^{\varphi}}{\varphi + 1}\right) \tag{1}$$

φ is the Pella-Tomlinson shape parameter, f is the relative fishing mortality rate ($f = \frac{F}{F_{MSY}}$) with F either equal to F_{MSY} or F_0, and b is the biological steady state relative to B_{MSY}, ($b = \frac{B}{B_{MSY}}$). We parameterized this model using values from Costello et al. (2016) to calculate biological steady state for current fishing mortality[2].

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

$$H = f \cdot b \cdot MSY \tag{2}$$

where f is the relative fishing mortality rate, b is the biological steady state for a given f (Eq. 1) and MSY is maximum sustainable yield for that fishery (extracted from Costello et al., 2016[2]).

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

$$Total\ cost = c \cdot (g \cdot f)^{\beta} + H \cdot management\ cost \tag{3}$$

where c is a fishery-level cost parameter (extracted from Costello et al., 2016[2]), g is a fishery-level growth parameter (extracted from Costello et al., 2016[2]), and f is the relative fishing mortality rate (determined by the scenario, either F_0 or F_{MSY}). β is a shape parameter ($\beta >$

1 means that additional fishing effort is increasingly costly); we assume that β equals 1.3 for all fisheries to reflect a (slightly) increasing marginal cost of effort[2]. H is steady state harvest determined by Eq. 2, and management cost is the cost of management per metric ton, which is based on a country-level database of management costs[15]. Management cost values were assigned based on (1) the country in which the fishery exists and (2) the type of management applied (i.e., broadly open access, strong catch controls, or catch shares). Fisheries that are 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 cost value under F_0 and the strong catch controls cost value under F_{MSY}. Multinational fisheries were assigned average values for each of the three management types.

Finally, under a range of prices $(0 - 20,000\frac{USD}{mt})$, we calculated profit for each fishing effort scenario (F_0 and F_{MSY}) using equation 4:

$$\pi = price \cdot H - total\ cost \tag{4}$$

H is steady state harvest for a given scenario (determined by equation 2), and total cost is the total cost for the scenario, defined by Eq. 3.

We included three supply curves for marine wild fisheries in our analysis. Each supply curve represents projected 2050 production at a given price. Importantly, we assume that distribution and processing are perfectly elastic and thus not a constraint to production. Previous research on the supply elasticity of fish processing sectors finds the sectors to be highly competitive and highly elastic[16]. The supply curves are:

1. **2050 production under current fishing pressure.** In this scenario, we assumed that all fisheries are managed under F_0. For each price, we determined if steady state production is profitable (if π from Eq. 4 is >0) for an individual fishery. Only fisheries for which production is profitable are assumed to be fished. Then, for each price, we aggregated the projected production in 2050 from all profitable fisheries.

2. **2050 production under rational reform.** In this scenario, we compared steady state profits between the two management scenarios (F_0 above and F_{MSY} below) for each individual fishery and at each price, and we assumed that the more profitable management decision F is applied. If neither scenario F_0 nor F_{MSY} resulted in profit

$\pi > 0$, we assumed that the fishery is not fished. Again, for each price we aggregated the projected production in 2050 from all profitable fisheries.

3. **2050 production under $\mathbf{F_{MSY}}$**. Under this reform, all fisheries adopt F_{MSY}, regardless of the cost. This represents a scenario in which eventually the maximum production potential is achieved for each individual fishery, even if it would be unprofitable in the absence of subsidies. For each price, we aggregated the projected production in 2050 from all fisheries.

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

- 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 for the harvesting sector. 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}.
- 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 gain to reform is comparatively small.
- The economic benefit from the fishery does not outweigh the cost of fishing.

Reform will initially lower food production as overfished fisheries recover – we find that under rational reform, global fisheries produce as much food as today in less than 10 years.

We test three scenarios as a sensitivity test for our rational reform supply curve. All four produce similar results (see fig. S1). The additional scenarios are:

Decreased extraction costs associated with improved technology. Technological improvements including the integration of artificial intelligence increase catchability and in effect decrease the cost of fishing. Therefore, we run a scenario in which extraction costs are reduced by 20%. This affects c in Eq. 3.

Increased management cost associated with reform. In this scenario, we apply the management cost associated with catch share management, which is greater than the cost associated with strong catch controls. This affects *management cost* in Eq. 3.

Both decreased extraction cost and increased management cost. In this scenario, we incorporate both of the scenarios described above.

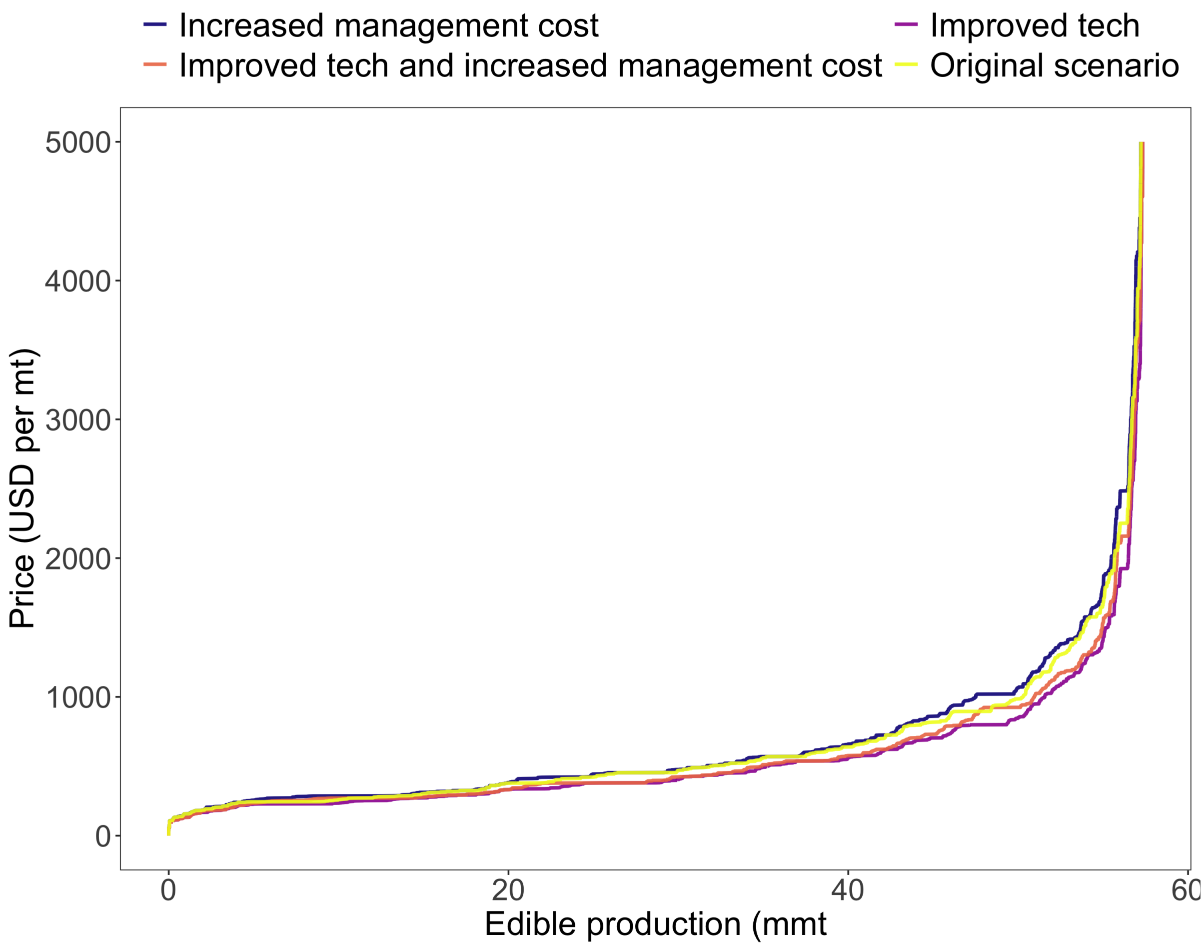

Figure S1: Marine capture supply curve under alternative technology and cost assumptions.

1.3 Mariculture Supply Curve

1.3.1 Overview

The potential for mariculture can be estimated as the biological potential constrained by (1) ocean zoning conflicts; (2) financial feasibility; (3) feed availability; (4) regulatory barriers[17,18]; and (5) other social barriers. Here, we estimated the potential for mariculture by accounting for constraints #1-2 and by evaluating feed availability scenarios and the role of regulatory barriers (constraints #3 and #4). Our supply curves do not explicitly account for social barriers such as public perceptions of mariculture sustainability[19]. The farm design used in the production model employs best practices for mariculture and thus represents sustainable design under current knowledge[20].

We used the Gentry et al. (2017) estimates of global mariculture potential to map the biological potential for ocean finfish and bivalve mariculture[20]. Gentry et al. (2017) excluded areas allocated for other uses (e.g., marine protected areas, major shipping areas, and oil rigs) as well as areas greater than 200 meters deep (which is cost-prohibitive), 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 mariculture (constraint #2). We evaluated the sensitivity of our results to the systematic under- or over-estimation of production costs (four scenarios: 25% overestimated, 50% underestimated, 100% underestimated, and perfectly estimated). We also evaluated four mariculture supply scenarios: a policy reform scenario under current feed requirements (constraint #4), and three technological innovation scenarios which affect the amount of finfish that can be produced from available fishmeal and fish oil (FM/FO) (constraint #3). These scenarios were repeated for three popular mariculture species' feed demands and market prices: Atlantic salmon, milkfish, and barrabundi.

This results in 48 mariculture scenarios for each marine wild capture fisheries scenario through the fully factorial combination of the following scenarios:

- 3 feed demands: salmon-like, milkfish-like, and barramundi-like
- 4 policy reform scenarios: policy reform, technological innovation, ambitious technological innovation, and full feed decoupling
- 4 production cost scalars: 0.75, 1, 1.5, and 2 times the estimated costs

1.3.2 Production Potential

Gentry et al. (2017) used a three-step approach to estimate the global production potential for finfish and bivalve mariculture. First, they calculated the growth potential for marine finfish ($n = 120$) and bivalve ($n = 60$) mariculture species in each 0.042 degree patch of ocean. They mapped the areas where each species could be farmed based on its thermal tolerance, and 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:

$$\phi_i = Log_{10}K_i + 2Log_{10}L_{\infty,i} \tag{5}$$

where $L_{\infty,i}$ is the asymptotic length (cm) and K_i is the growth coefficient (yr^{-1}) from the von Bertalanffy individual growth equation for species i.

Second, they calculated the production potential for finfish and bivalve mariculture by making straightforward assumptions about farm design (Table S4) 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)[21]. 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 ($\frac{mt}{year}$), P_p, for patch p was then calculated as:

$$P_p = \frac{(N_{fish} \cdot B_{market})}{T_{market,p}} \cdot A_p \tag{6}$$

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 factors. They excluded finfish areas with average growth performance indices below 2.0

or annual dissolved oxygen concentrations below the sub-lethal limit for finfish ($4.41\frac{mg}{l}$). They excluded bivalve areas with average growth performance indices below 1.0, annual chlorophyll a concentrations below $2.0\frac{mg}{m^3}$, or more than two months per year with chlorophyll a concentrations below $1.0\frac{mg}{m^3}$. They also excluded areas in waters greater than 200 meters in depth – these areas are too deep and expensive to anchor, oversee, and operate farms – and areas already allocated to marine protected areas, oil rigs, and high-density shipping lanes.

Parameter	**Value**
Finfish farm (1 km2)	
Specifications:	
Number of cages	24
Cage volume (m3)	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
Bivalve farm (1 km2)	
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

Table S4: Finfish and bivalve farm specifications from Gentry et al. (2017)[20].

1.3.3 Production Costs

The total annual cost (C_{total}) of mariculture 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 ($C_{operations}$):

$$C_{total} = C_{capital} + C_{fuel} + C_{labor} + C_{operations} \tag{7}$$

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 S5) and bivalve (Table S6) mariculture 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 ($V_{efficiency}$)[22]. 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[23]. Thus, annual fuel cost for each patch of ocean was calculated as:

$$C_{fuel} = \frac{2 \cdot T_{dist}}{V_{speed}} \cdot V_{efficiency} \cdot F_{price} \cdot V_{trips} \cdot N_{farms} \tag{8}$$

where the number of farms (N_{farms}) per patch was determined by the area of the patch.

Annual labor costs (C_{labor}) were calculated assuming that each farm requires eight people (W_{number}) working 2,080 hours per year (H_{fixed}; 40 hours per week * 52 weeks) in addition to the hours required for round-trip transits ($H_{transit}$) (Table S7). Worker wages (W_{wages}) were based on country-specific averages from the World Bank (2019b)[24]. Round-trip transit time was calculated using the vessel speed and the number and distance of trips:

$$H_{transit} = \frac{2 \cdot T_{dist}}{V_{speed}} \cdot V_{trips} \tag{9}$$

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

$$C_{feed} = (AQ_{prod} \cdot FCR) \cdot F_{price} \tag{10}$$

where the annual feed requirement 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[20].

This model gives rise to finfish production costs that are comparable to those reported by Iversen et al. (2019) for Atlantic salmon[25]. Additionally, we explored the sensitivity of our results to the possibility of systematically over- or under-estimating production costs (0.75, 1, 1.5, or 2 times the model estimated costs).

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	
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 S5: Cost parameters for finfish aquaculture from Rubino 2008[26]

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 S6: Cost parameters for bivalve aquaculture from Rubino 2008[26]

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 S7: Cost parameters common to both finfish and bivalve aquaculture

1.3.4 Mariculture Supply Scenarios

We examined four sustainable mariculture supply scenarios: one policy reform scenario under current feed requirements and three technological innovation scenarios. All four scenarios represent a future in which regulatory barriers are removed and unsustainable production is prevented. In such a future, the potential for finfish mariculture 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 (e.g., soya beans, livestock by-products, cotton seeds, etc.). The fishmeal and fish oil (FM/FO) portions of feed may be manufactured from whole fish from fisheries that are fully or partially dedicated to feed production (i.e., reduction fisheries targeting forage fish), from by-products (a.k.a., trimmings or waste) from fisheries targeting fish for human consumption, or from by-products from aquaculture. 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 produced. 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 decreasing the amount of wild fish required to produce a unit of maricultured fish, a quantity known as the "Fish In, Fish Out" (FIFO) ratio. Technological innovations in feed ingredients and feed efficiency will reduce the amount of FM/FO needed to produce fed mariculture. As such, we evaluated four mariculture supply scenarios:

1. **Policy Reform Scenario (Scenario 1)**: FM/FO is produced from both the by-products of capture fisheries and whole fish from directed reduction fisheries at current rates. This scenario represents a case with current feed production technology, but substantial policy reform that allows for sustainable mariculture expansion into currently profitable waters.

2. **Technological Innovation Scenario (Scenario 2)**: FM/FO is produced from both by-products and whole fish as in Scenario 1, but the FM/FO requirement of feed is reduced by 50% to reflect the potential for fish ingredients to be replaced by alternate ingredients in the near future.

3. **Ambitious Technological Innovation Scenario (Scenario 3)**: FM/FO is produced from both by-products and whole fish as in Scenario 1, but the FM/FO requirement of feed is reduced by 95% to reflect the potential for fish ingredients to be replaced by alternate ingredients in the near future.

4. **Full Feed Decoupling Scenario (Scenario 4)**: FM/FO is completely replaced by alternate ingredients in the near future – no by-products or whole fish are needed from wild fisheries to support mariculture.

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)[27]. Otherwise, the scenarios are informed by the present day proportion of capture landings dedicated to FM/FO production (18% in 2010[5]) and proportions of fishmeal and fish oil committed to mariculture (73% and 80%, respectively[28]). These scenarios are designed to capitalize on the full potential for by-products to support finfish mariculture 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. Scenarios 1-3 are presented in the main text supply figures, and Scenario 3 is used for Fig. 5. Scenario 4 is not included in the main text, but it is considered in sensitivity analyses (see Section 1.5).

1.3.5 Feed ingredients from by-products

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 (Table S8)[27]. 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 mariculture. They show that capture fisheries currently produce 3.7 million mt 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 mt of fishmeal and 158,000 mt of fish oil.

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 mariculture fisheries combined[27]. 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 the 26.4% and 4.2% 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.

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:

$$FM_p = WC_p \cdot 0.069 \tag{11}$$

$$FO_p = WC_p \cdot 0.011 \tag{12}$$

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[28]. Thus, the fishmeal ($FM_{AQ,p}$) and fish oil ($FO_{AQ,p}$) available for mariculture from the by-products of capture fisheries at price p is:

$$FM_{AQ,p} = FM_p \cdot 0.73 \tag{13}$$

$$FO_{AQ,p} = FO_p \cdot 0.80 \tag{14}$$

We determined how much fish feed ($Feed_p$) could be produced from these quantities based on the proportion of feed composed of fishmeal ($pFM_{s,r}$) and fish oil ($pFO_{s,r}$) for species s in policy reform scenario r, and given that either ingredient could limit the availability of feed:

$$Feed_{FO,s,r,p} = \frac{FO_{AQ,p}}{pFO_{s,r}} \tag{15}$$

$$Feed_{FM,s,r,p} = \frac{FM_{AQ,p}}{pFM_{s,r}} \tag{16}$$

$$Feed_{s,r,p} = min\left(Feed_{FO,s,r,p}, Feed_{FM,s,r,p}\right) \tag{17}$$

We determined how much finfish mariculture (FAQ_p) this amount of feed could support using the feed conversion ratio for species s (which does not vary by policy scenario):

$$FAQ_{s,r,p} = Feed_{s,r,p} \cdot FCR_s \tag{18}$$

See Table S9 for the FCR for each species (Atlantic salmon, milkfish, and barramundi) and their feed compositions under each policy reform scenario. The results presented in the main text reflect the 'feed conditions' of Atlantic salmon[29] which accounts for 34% of marine fed-finfish production and is one of the most well studied fed species in the literature.

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 S8: 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)[27]

Scenario	FCR	% FM in feed	% FO in feed	FIFO	Mariculture (mt) from 1 mmt of capture
Atlantic salmon					
Policy reform scenario	1.15	18.3%	10.9%	1.23	0.81
Technological innovation scenario	1.15	9.2%	5.5%	0.62	1.62
Ambitious technological innovation scenario	1.15	0.9%	0.5%	0.06	16.23
Milkfish					
Policy reform scenario	1.5	1.0%	0.5%	0.08	12.11
Technological innovation scenario	1.5	0.5%	0.3%	0.04	24.22
Ambitious technological innovation scenario	1.5	0.1%	0.0%	0.00	242.22
Barramundi					
Policy reform scenario	1.5	8.0%	3.0%	0.61	1.65
Technological innovation scenario	1.5	4.0%	1.5%	0.30	3.30
Ambitious technological innovation scenario	1.5	0.4%	0.2%	0.03	33.03

Table S9: Fish in-fish out ratios implemented in each scenario and the amount of mariculture production produced from 1 million mt of capture fisheries landings (whole fish). The FCR and FM/FO composition for Atlantic salmon is from Ytrestøyl et al. (2015) and the FCRs and FM/FO compositions for milkfish and barramundi are from Tacon and Metian (2015)[29,30].

1.3.6 Feed ingredients from capture fisheries harvested from reduction industry

The review of Cashion et al. (2017) indicates that approximately 18% of capture landings are directed to FM/FO production[5]. Thus, we calculated the amount of landings available for FM/FO production from whole fish ($WC_{whole,p}$) at price p as:

$$WC_{whole,p} = WC_{p,i} \cdot 0.18 \tag{19}$$

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[27]:

$$FM_{whole,p} = WC_{whole,p} \cdot 0.224 \tag{20}$$

$$FO_{whole,p} = WC_{whole,p} \cdot 0.0485 \tag{21}$$

The production of fishmeal and fish oil from the by-products of the landings not directed to whole fish reduction was then calculated as follows (recall values 0.069 and 0.011 from equations 11 and 12):

$$FM_{by,p} = (WC_p - WC_{whole,p}) \cdot 0.069 \tag{22}$$

$$FO_{by,p} = (WC_p - WC_{whole,p}) \cdot 0.011 \tag{23}$$

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

$$FM_p = FM_{whole,p} + FM_{by,p} \tag{24}$$

$$FO_p = FO_{whole,p} + FO_{by,p} \tag{25}$$

The amount of finfish mariculture that can be supported by these amounts of ingredients was calculated using the process described by Equations 13 through 18 above.

1.3.7 Reductions in the FM/FO requirement 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 1 except that the

FM/FO requirements of feed were reduced by 50% or 95% (2 sub-scenarios) to reflect the potential for fish ingredients to be replaced by alternate ingredients in the near future.

1.3.8 Scenario 4: FM/FO availability is not limiting

In this scenario, mariculture feed is assumed to be composed of entirely non-fish ingredients and finfish mariculture is therefore unconstrained by capture fisheries production. The cost of feed is assumed to be the same as present day feed. This scenario is not presented in the main text figures.

1.3.9 Fish In, Fish Out ratios implemented in each feed scenario

We derived the fish in-fish out (FIFO) ratio implemented in each scenario using the following equation from Jackson (2009)[31]:

$$FIFO = FCR \cdot \frac{\textit{Level of FM in feed} + LevelofFOinfeed}{\textit{Yield of FM from whole fish} + \textit{Yield of FO from wild fish}} \tag{26}$$

where the feed conversion ratio (FCR) varies by species (Table S3), the percent of fishmeal (FM) and fish oil (FO) in feed varied based on the technology scenario (Table S9), and the yields of fishmeal and fish oil from whole fish were 22.4% and 4.85%, respectively[27]. For Atlantic salmon, the species whose results are featured in the main text, this results in a FIFO ratio of 1.23 under current feed technology and FIFO ratios of 0.62 and 0.06 with 50% and 95% reductions in the inclusion of fish ingredients in feed (technological innovation scenarios). These FIFO ratios imply that 1 mt of capture fisheries landings would result in 0.81 mt of maricultured finfish under current technology but 1.62 and 16.23 mt of maricultured finfish with technological advances (Table S9). See Table S9 for the FIFOs and yields for the other two species.

1.3.10 Estimating supply curves for bivalve and finfish mariculture sectors

We generated a supply curve for each mariculture sector (finfish and bivalves) by summing the production potential of cells that would be profitable at each price (USD 0-20,000 per mt). We allow for both finfish and bivalve mariculture to occur in the same patch given the ecological benefits of multi-trophic mariculture production. We converted whole fish production to production of edible meat using the same conversion ratios as in capture fisheries: 87% for finfish and 17% for bivalves. Again, we assume that distribution and processing are perfectly elastic and thus not a constraint to production[16] (see Section 1.2 for additional discussion and Section 1.3.1 for a discussion of sensitivity analysis with regards to the costs of production).

1.3.11 Evaluating the role of regulatory barriers

We evaluated the role of regulatory barriers by comparing current mariculture production obtained from FAO 2018 to the quantity that would be supplied according to the estimated supply curve at current prices[32]. These results appear in the main text and are the reason that current production differs from the Policy Reform scenario.

1.4 Inland Production Supply Curve

In order to understand the future of food from the sea, it is vital we consider the future of land-based fisheries, both capture and aquaculture. While inland aquatic foods production is not the focus of this work, it is a necessary component of effectively contextualizing the future demand for marine foods. To do so, we built supply curves for inland fisheries and aquaculture that cover all inland production. Dey et al. (2008) report supply elasticity estimates for a range of aquatic species[33]. Importantly, they report elasticities disaggregated by production method, spanning: inland capture, inland culture, marine capture, and marine culture. Because the majority of our analysis has focused on novel methods for deriving the supply curve of marine fish, we avoided using Dey et al. (2008) in regards to marine production. Instead, we used the estimates of inland production across species and production type to characterize an aggregate supply curve of inland fisheries production.

1.4.1 Aggregation of inland product classes

Many species are produced via inland aquaculture and capture. However, treating species individually is difficult due to the lack of data availability with regard to key modeling inputs such as price and price elasticity of supply. For inland aquaculture, the majority of production (roughly 84%) is of carp, tilapia, and catfish. The majority of inland capture fisheries landings is classified as the miscellaneous group "freshwater fish not elsewhere included" by the FAO[1]. Of the species that are classified, however, 26% of landings are comprised of carp, tilapia, and catfish. As such, we characterized supply curves for four inland capture and inland aquaculture categories: carp, tilapia, catfish, and an aggregate category for *other* inland production. To generate these four categories, we used ISSCAAP categories where possible and elsewhere classify based on key words for both the scientific and common names of species. All species not included in either the carp, tilapia, or catfish category were aggregated in the *other* category. Product groups were also categorized by their production method, either aquaculture or capture. A necessary assumption in this case is that within each product category, the species are perfect substitutes in demand. Below we present the method for generating an aggregate supply curve for inland aquaculture and inland capture for each product category.

1.4.2 Inland aquaculture supply curve

We modeled the supply of inland aquaculture as the aggregate supply from our four product categories: carp, tilapia, catfish, and other. We modeled inland supply of aquaculture using an isoelastic supply function with exogenous growth, with functional form:

$$Q_c = A_c p^{\epsilon_c} \tag{27}$$

where Q_c is the quantity of food supplied in product category c, A is a product category specific supply multiplier, p is the price of the product, and ϵ_c is the supply elasticity in product category c. In order to accurately estimate supply curves of this form, we need estimates of the price elasticity of supply for each product category, as well as current production quantities and prices for each product category. Here we report elasticity estimates for inland capture and culture adapted from Dey et al. We only report the averages for each species and direct the reader to Dey et al. (2008) for further discussion[33]. For a discussion of the prices used, see section 1.1.7. Estimation of production quantities are described in section 1.1.1 and conversion rates are discussed in section 1.1.5. Table S10 outlines the inland aquaculture supply elasticities used in this analysis. Further, we conduct sensitivity analyses using a range of supply elasticities, discussed in section 1.4.4, with results presented in section 2.

Production from inland aquaculture has been growing over the last several decades. Increase in production is a function of a myriad of factors such as changes in technology, policy, and environmental factors. We adopted constant growth rates for each product class. We estimate growth using FAO time series data and assume the constant growth rate is equal to the average growth rate over the last five years (2013 - 2017). The estimated growth rates are presented in table S11.

Estimated growth rates are applied to the baseline supply curve in order to increase production at every price by the estimated growth. As a result, supply at time t+1 can be represented as:

$$Q_{t+1} = (1 + g_c)A_c p^{\epsilon_c} \tag{28}$$

where g_c is the growth rate of product cateogory c. We also conduct sensitivity analysis with regards to the estimated growth rates, discussed in section 1.4.4, with results presented in section 2.

Species	Inland Aquaculture Supply Elasticity
Carp	0.60
Tilapia	0.24
Catfish	1.08
Other	0.27

Table S10: Inland aquaculture supply elasticities by product group augmented from Dey et al. (2008)[33]

Product Category	Five Year Average Growth Rate
Carp	1.5%
Tilapia	2.45%
Catfish	1.96%
Other	1.7%

Table S11: Average growth rates by product category for inland aquaculture production. Estimated from FAO aquaculture production data.[1]

1.4.3 Inland capture fisheries supply curve

Similar to inland aquaculture, the majority of global inland capture production is an aggregate of many individual species. As a result, we used the same species categories used above for inland aquaculture: carp, tilapia, catfish, and *other*. Capture fisheries are subject to biological limits and complex economic incentives for harvesting depending on the costs of fishing, the management of the specific stock, and the underlying available biomass. In the main text, we assume that inland fisheries capture is constant. This assumption is justified by the unclear impacts on harvest of additional future demand, technological change, and management effectiveness. Similar to marine fisheries, inland fisheries likely have a backward bending supply curve in open access presented in figure 1 of the main text. Furthermore, the quantity-weighted average growth of inland capture over the last five years is less than 1%. This is consistent with modeling supply as being completely inelastic.

It is still possible that inland capture fisheries are price responsive. As a result, we subsequently modeled inland capture supply using isoelastic supply functions similar to those presented in section 1.4.2. Table S12 presents supply elasticity estimates augmented from Dey at al. (2008) for inland capture[33]. We used the prices described in section 1.1.7 as well as the current production quantities discussed in section 1.1.3 to estimate a supply curve specific to product categories.

Species	Inland Capture Supply Elasticity
Carp	0.8
Tilapia	0.18
Catfish	0.28
Other	0.62

Table S12: Inland capture supply elasticities by product group. Augmented from Dey et al. (2008).[33]

1.4.4 Generating Inland Aquatic Supply Curves

Above, we outlined how we generate product category supply curves for both inland aquaculture and inland fisheries capture. Similar to the other sectors modeled in this research, we treat the products of inland aquatic food supply as perfect substitutes. As such, we can horizontally aggregate the product category supply curves to generate a supply curve for inland aquaculture and inland capture. Horizontal aggregation of the inland capture and inland culture supply curves, under the assumption of perfect substitutability of inland seafood, results in a total inland aquatic foods supply curve.

We conducted several robustness checks to uncover the potential sensitivity of the inland aquatic foods supply curve to key parameters and assumptions. We investigated the following scenarios regarding inland production, with results presented in section 2:

- *A high, medium and low growth scenario for inland aquaculture:* The medium scenario uses estimated growth rates as per table S11. High growth rates assumes a growth rate twice as large as those presented in table S11 while the low growth rate scenario assumes no exogeneous growth in aquaculture production. See section 1.4.2) for further discussion.
- *A high, medium, and low supply elasticity scenario for inland aquaculture:* The medium scenario uses estimated elasticities from Dey et al. (2008)[33] listed in Table S10. The high elasticity scenario assumes a supply elasticity 50% larger than those presented in Table S10 while the low scenario uses an elasticity 50% smaller than those presented in Table S10. See section 1.4.2) for further discussion.
- *Price responsiveness of inland capture fisheries:* This scenario assumes inland capture fisheries are price responsive rather than subject to a constant harvest over time. See section 1.4.3 for further discussion.

1.5 Supply Curve Scenarios

1.5.1 Independent Sectors Scenario

In this scenario, which is the one highlighted in the main text, we assume that the three food from the sea sectors, and the inland supply sector, are independent. In this setting, each sector has an independent supply and demand curve and the intersection of those curves could occur at different prices. Wild fishery production and finfish mariculture production are still linked via feed. The amount of FM/FO available to the finfish sector directly depends on wild fishery production. The amount of wild harvest directed to feed production is very similar for all three of our demand scenarios (the difference equals 1 mmt). Although production would be capped based on this amount, it does not affect the finfish production results because the demand curves intersect supply much earlier than that cap would.

1.5.2 Perfect Substitutes Scenario

In section 2, we show the results for this alternative scenario, in which we assume that production from the three marine sectors and the inland sector are perfect substitutes. This could reflect, for example, a future in which aquatic proteins are viewed as completely interchangeable. Under that assumption, the supply curves derived above can be horizontally aggregated to derive a global supply curve of aquatic foods. Thus, we horizontally aggregated the supply curves from all three food from the sea sectors to generate an overall supply curve of food from the sea. We then add this overall supply curve of food from the sea with the inland supply curve to generate a global supply curve of aquatic foods.

In all scenarios, production of whole fish was converted to production of edible meat using the mean conversion ratios from Edwards et al. (2019)[7] for finfish, crustaceans, and molluscs, and conversions based on these values for echinoderms and miscellaneous invertebrates. See section 1.1.5 for more details regarding these conversion rates.

1.6 Demand curves

The previous sections describe our methods for constructing supply curves for wild fisheries, mariculture and inland capture and culture. Supply curves show a quantity supplied for any given price of the good in question. However, to assess plausible quantities of food supplied from the sea and the inland aquatic sector, we must examine the intersection between supply and demand. While this paper is not explicitly about deriving demand curves of food from the sea, we would like to invoke plausible demand estimates for projection purposes.

To generate plausible future demand scenarios, we started with a simple model of consumer demand for fish. Under the assumption that demand for finfish and unfed mariculture, marine capture fisheries, and inland aquatic foods are independent (see above), for each sector j, we assumed that the quantity demanded is defined as follows:

$$D_j = \alpha_j N p_j^{\beta_j} y^{\gamma_j} \tag{29}$$

where α_j is a demand shift parameter (scalar for sector j), N is the global population of people, p_j is the price of fish in sector j (USD per mt, viewed as a variable), β_j is the price elasticity of demand in sector j, assumed to be constant across sectors (as per Cai et al. (2017)[34]), y is the global per capita income, and γ_j is the income elasticity of demand for sector j.

For each sector, we assumed a global representative consumer with known income, y, (the global average per capita income, which we proxied with per capita GDP: 17,117 USD as estimated by The World Bank (2017)[35]), and known price and income elasticity, β and γ_j. We used global population estimates from IMF (2017) to estimate N[35,36]. We used a global mean price elasticity of demand equal to -0.38 consistent with Muhammed et al. (2013) and Lem et al. (2014)[37,38]. We used the mean value of income elasticity of demand for marine finfish from Cai et al. (2017) ($\gamma = 0.564$) for the wild fisheries demand and finfish mariculture demand. For unfed mariculture demand, we used the mean value of the income elasticity of demand for shelled molluscs ($\gamma = 1.06$) from Cai et al. (2017)[34]. For land based fisheries, we use the mean value of the income elasticity of demand for freshwater & diadromous fish ($\gamma = 0.41$) from Cai et al. (2017)[34].

For the "Perfect Substitutes" model (where sectors are aggregated), we take the weighted average of the income elasticities of demand (weighted by current production). The values are $\gamma = 0.59$ when only marine food sectors are included and $\gamma = 0.51$ when all four sectors (i.e., marine capture, finfish mariculture, bivalve mariculture, and inland production) are included.

We then calculated α_j using a global price of seafood in each sector (see section 1.1.7) and quantity supplied estimated from Costello et al. (2016)[2], where:

$$\alpha_j = \frac{D}{N p_j^{\beta} y^{\gamma_j}} \tag{30}$$

With calculated α_j parameters then held fixed, we are able to model demand for any population, N, with per capita income, y, using Eq. 29. Accordingly, we modeled three demand scenarios: a current demand scenario, a future demand scenario, and an extreme demand scenario:

1. **Current Demand Scenario**: current global population and per capita income
2. **Future Demand Scenario**: expected global population and per capita in 2050

3. **Extreme Demand Scenario**: a doubling of the quantity demanded at any given price as compared to the Future Demand Scenario

The current demand scenario uses the current global population estimate and per capita income estimate mentioned above. The future demand scenario requires estimates of population and GDP in 2050. The UN estimates the global population in 2050 to be 9.8 billion[35]. Cumulative global GDP growth is expected to be 130% between 2016 and 2050[39]. We divide 2050 global GDP by projected population to estimate future GDP per capita. Accordingly, the implied demand curve in 2050 is:

$$D_j = \alpha_j(9.8 * 10^9)(28484)^{\gamma_j} p_j^{\beta} \tag{31}$$

To create the extreme demand scenario, we multiplied the estimated demand equation for each sector in 2050 (presented in Eq. 31) by 2. This represents a doubling of the quantity demanded at any given price as compared to the future demand scenario.

1.7 Results across all demand and substitution scenarios

Taken together, this analysis considers four aquatic food sectors (marine wild capture, finfish mariculture, bivalve mariculture, and inland fisheries), two substitution scenarios (independent sectors and perfect substitutes), and three demand scenarios (current demand, future demand, and extreme demand). Figure S2 highlights the perfect substitutes scenario (not shown in the main text) with four panels. The top two panels show the aggregated supply curves (aggregated across all four sectors) under policy reforms and under ambitious technological innovation. The colors show the contribution to global aquatic food supply from each sector. The bottom panels show the aggregated supply and demand curves.

Figure S3 shows the equilibrium quantities from our supply and demand analysis across the full range of scenarios described above (along with current production in each sector). The left-hand panel shows results for the independent sectors scenario. The only difference between this left panel and Figure 5 in the main text is that we have included inland fisheries in this figure.

The data underlying Figure S3 are given in Tables S13 and S14, respectively for the independent sectors scenario and the perfect substitutes scenario.

As discussed in detail, our paper presents production values as actual food, not as fish landings. But because many reports focus on fish landings, here we reproduce Tables S13 and S14 in terms of raw landings directed to human consumption (in corresponding Tables S15 and S16).

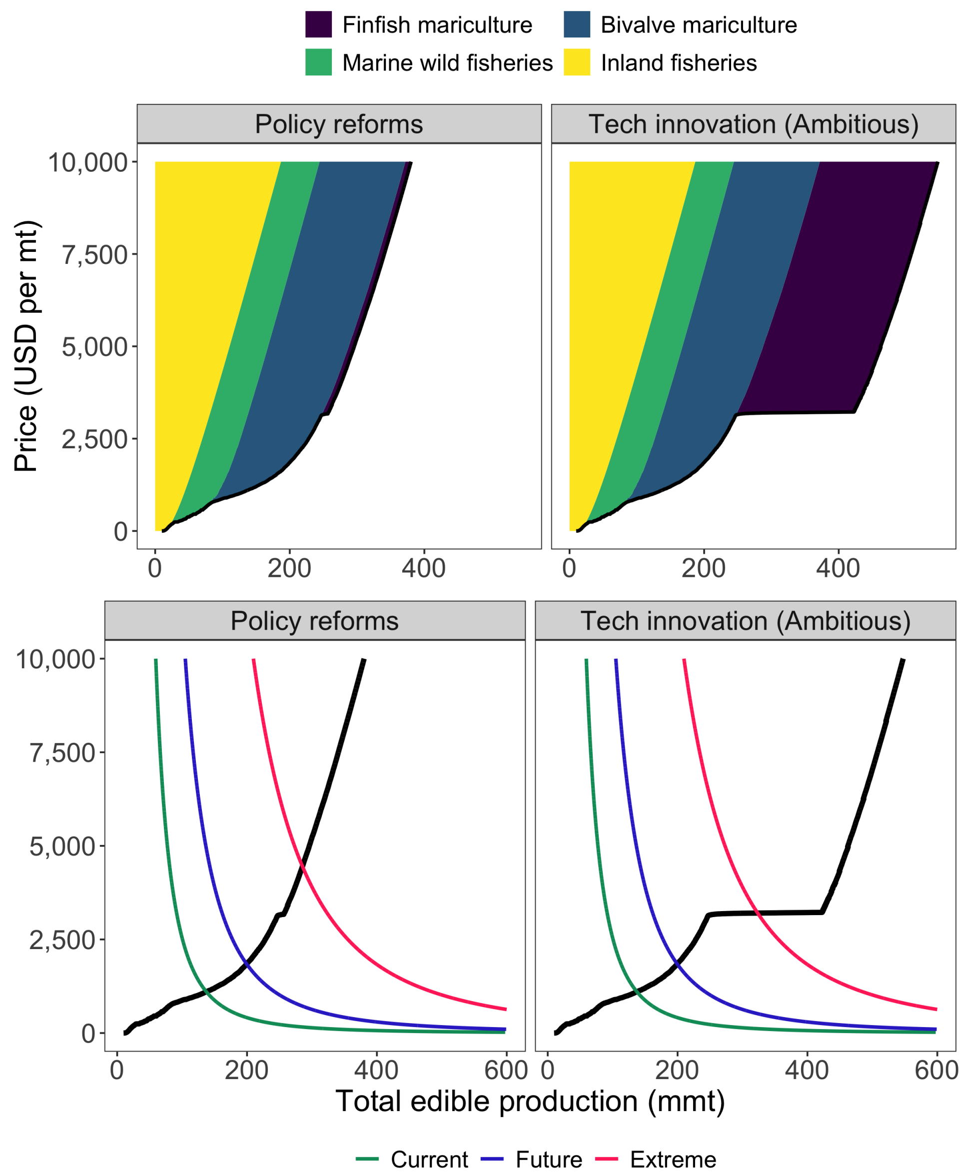

Figure S2: Aggregate supply curve (black line) and demand curves (bottom panel, color lines) for all four aquatic foods sectors under the perfect substitutes scenario.

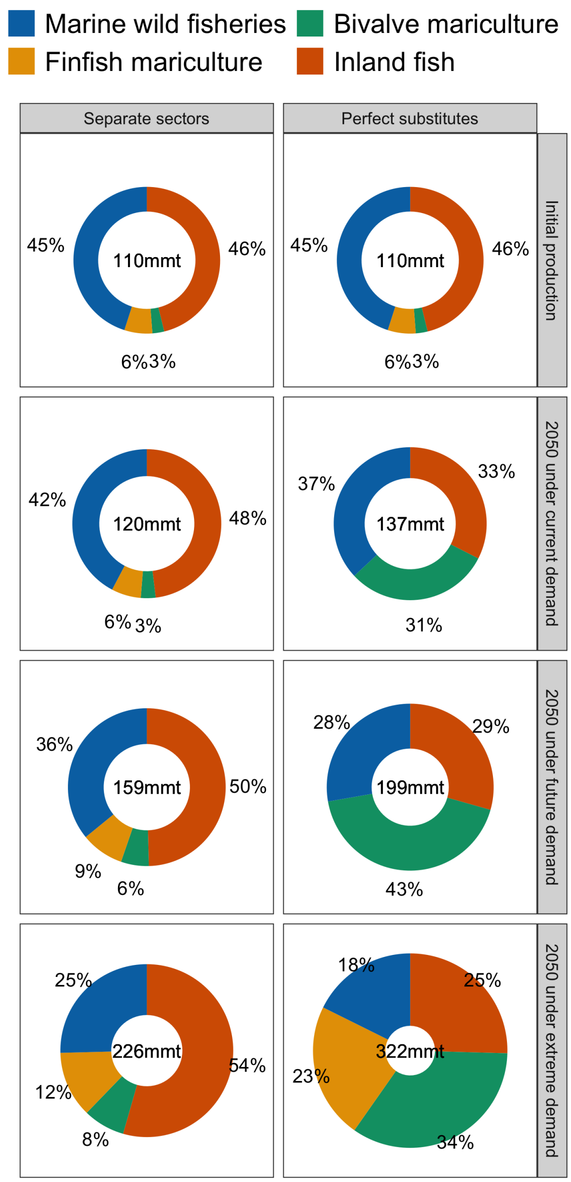

Figure S3: Donut plots for independent sectors (left panel) and perfect substitutes (right panel). All four sectors (including Inland fisheries) are shown. Left panel is identical to what is shown in main text, but this plot also includes Inland fisheries for comparison.

Sector	Initial	Current Dem.	Future Dem.	Extreme Dem.
Marine wild	49.44	50.60	57.03	57.41
Finfish mar.	6.77	7.67	13.98	27.94
Bivalve mar.	2.86	3.85	9.07	17.61
Inland fisheries	50.68	57.55	78.77	122.98
Total	109.74	119.67	158.86	225.94

Table S13: Data for the donut plot in the main text (independent sectors scenario), also including food from Inland fisheries (aquaculture and capture). All values are expressed in mmt.

Sector	Initial	Current Dem.	Future Dem.	Extreme Dem.
Marine wild	49.44	50.75	55.35	56.83
Finfish mar.	6.77	0.00	0.00	72.69
Bivalve mar.	2.86	41.97	85.48	110.32
Inland fisheries	50.68	44.66	58.61	81.81
Total	109.74	137.39	199.43	321.65

Table S14: Data under the donut plot in the perfect substitutes scenario. All values are expressed in mmt.

Sector	Initial	Current Dem.	Future Dem.	Extreme Dem.
Marine wild	77.36	76.19	88.43	89.30
Finfish mar.	7.78	8.82	16.08	32.13
Bivalve mar.	17.17	23.09	54.44	105.69
Inland fisheries	60.96	67.12	93.60	149.64
Total	163.27	175.21	252.55	376.76

Table S15: Data under the donut plot, but converted back to live-weight equivalents (i.e., landings, not food) for the independent sectors scenario. All values are expressed in mmt.

Sector	Initial	Current Dem.	Future Dem.	Extreme Dem.
Marine wild	77.36	76.48	85.07	87.99
Finfish mar.	7.78	0.00	0.00	83.59
Bivalve mar.	17.17	251.84	512.86	661.91
Inland fisheries	60.96	51.25	68.43	97.42
Total	163.27	379.57	666.37	930.91

Table S16: Data under the donut plot, but converted back to live-weight equivalents (i.e., landings, not food) in the perfect substitutes scenario. All values are expressed in mmt.

2 Sensitivity Analysis

Our model and results have relied on a large number of assumptions and scenarios. Because our supply and demand models are complex and non-linear, it is not immediately apparent how any given assumption, or combinations of assumptions, will affect our final results.

Our main results pertain to the equilibrium production of food from the four aquatic food sectors (including inland fisheries) in 2050. In this section we report on the distribution of those outcomes under a large range of scenarios. These scenarios include:

- Six scenarios for inland fisheries production (see Section 1.4.4)
- Three additional scenarios (in addition to what is report in the main text) for marine capture fishery cost and technology (see Section 1.2)
- Two additional scenarios of finfish mariculture species (see Section 1.3.1)
- Three additional mariculture cost scenarios (see Section 1.3.1)
- Five mariculture policy scenarios (see Section 1.3.1)
- Two substitution scenarios (see Section 1.5.2 and Section 1.5.1)

These scenarios are described in the relevant sections above. When considering all possible scenarios across all four sectors, this amounts to over 10,000 unique combinations of model assumptions. Our approach was to run the exhaustive set of every combination.

Figure S4 shows the outcome of the sensitivity analysis, and is organized as follows. Each row represents a sector of the aquatic food economy in 2050 (including a fifth row, which is the total amount of food after summing all sectors). For each sector we plot the statistical distribution of 2050 production under the full suite of scenarios described above. We show two distributions for each sector: One for the independent sectors scenario and one for the perfect substitutes scenario. This allows the reader to examine how the substitution scenario alters likely production. For example, we find that marine capture fisheries are largely insensitive to substitution across sectors. In contrast, we predict that the bivalve mariculture sector will produce substantially more food if future food demand treats all aquatic foods as perfectly substitutable.

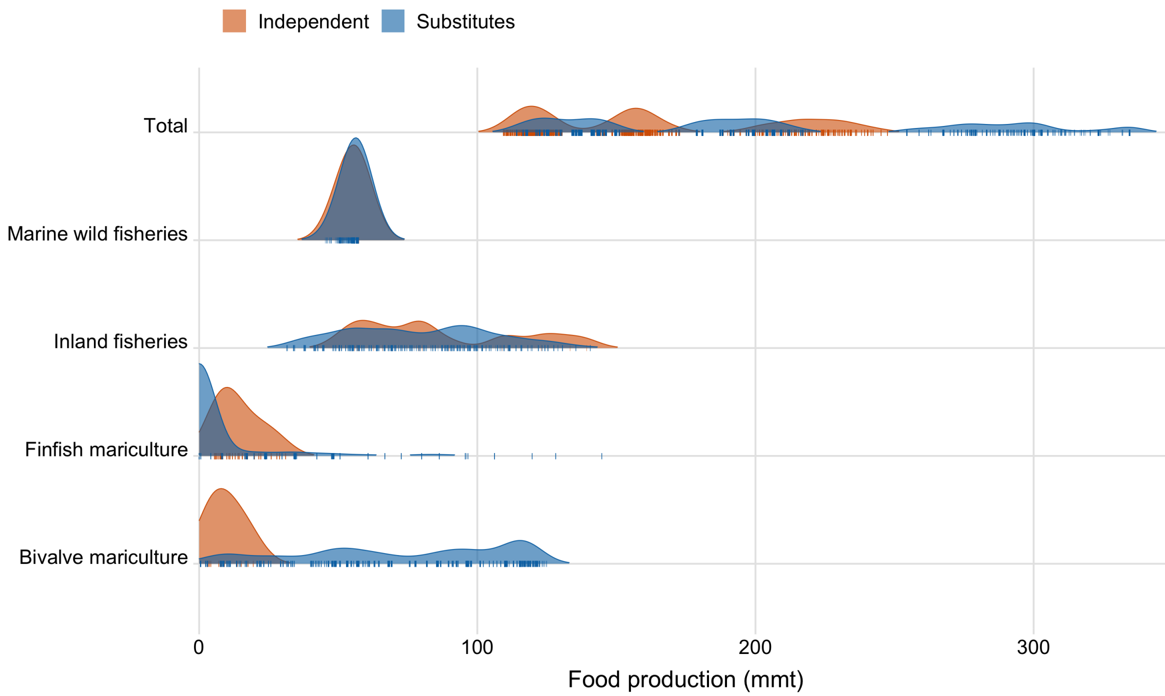

Figure S4: Sensitivity analysis ridges plot, which depicts the distribution of sensitivity analysis results for each sector across the full range of scenarios. Tick marks on axis show individual scenario outcomes.

Table S17 extracts the mean across all scenarios. The second column of Table S17 (Independent sectors assumption) can be compared against the results from the analysis reported in the main text (also summarized in the last two columns of Table S13). This reveals that the mean values from the sensitivity analysis are within a few percent of the results from the analysis reported in the main text.

Sector	Mean Food (Indep.)	Mean Food (Subst.)
Bivalve mar.	9.54	72.08
Finfish mar.	13.98	6.89
Inland fisheries	87.12	79.48
Marine wild	55.17	56.02
Total	165.81	207.07

Table S17: Mean food production in 2050 for each sector across all scenarios represented in the sensitivity analysis.

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