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Supplementary information

Expanding ocean food production under climate change

In the format provided by the authors and unedited

Supplementary Methods

1. Overview

We combined projections of human population growth[1], marine fisheries production[2], and mariculture production to ask whether coordinated policy, technology, and management reforms in marine fisheries and mariculture could jointly increase global and national seafood production *per capita* under climate change (RCPs 2.6, 4.5, 6.0, and 8.5; **Supplementary Table 4**). Forecasts of fisheries production are based on the climate-linked bioeconomic model results of Free et al.[2] and present production outcomes under two fisheries management scenarios (**Supplementary Tables 5-6**): (1) business-as-usual (BAU) management, in which current (and often suboptimal) harvest rates degrade to open access as stocks shift into new management areas; and (2) climate-adaptive management, in which economically optimal harvest rates are maintained as stocks shift into new management areas. We forecasted mariculture production potential using a climate-linked input-output model that accounts for the joint constraints of environmental suitability, competing ocean uses, economic feasibility, availability of feed for fed-mariculture (which depends on fisheries production), and consumer demand[3] (**Supplementary Tables 1-2**).

We explored two cross-sector policy scenarios: (1) a business-as-usual scenario, in which the availability of the forage fish used for mariculture feed is determined based on BAU fisheries management and the efficiency with which forage fish are converted to farmed fish is based on moderate advances in feed technology (2030 FIFO ratios; **Supplementary Table 7**); and (2) a progressive reforms scenario, in which the availability of forage fish is determined based on climate-adaptive fisheries management and the efficiency with which forage fish are converted to farmed fish is based on progressive advances in feed technology (2050 FIFO ratios; **Supplementary Table 7**). To quantify the food potential of fisheries and mariculture[4], we converted fisheries landings and mariculture production from their live-weight values to their edible meat equivalents using group-level conversion factors[5] (**Supplementary Table 8**). Finally, we calculated seafood production *per capita* using global and national population projections[1] (**Supplementary Fig. 1**). All analyses were performed using the R computing software[6] and all code is available here: https://github.com/cfree14/aquacast

2. Fisheries analysis

We used the Free et al.[2] climate-linked fisheries bioeconomic model to examine global and coastal country-level changes in seafood production from marine fisheries under four climate change scenarios (RCPs 2.6, 4.5, 6.0, 8.5; **Supplementary Table 4**) and two fisheries management scenarios from 2012 to 2100. Free et al.[2] evaluated 779 harvested marine fish and invertebrates whose initial distributions were determined based on AquaMaps[7] and whose initial biomasses, fishing mortalities, and statuses (B/B_{MSY}) were determined based on Costello et al.[8]. They then projected changes in distribution and productivity through the following general procedure: (1) distributions were updated using a bioclimatic envelope model[9]; (2)

productivity was assumed to change in proportion to changes in range size, i.e., a 10% increase in range size results in a 10% increase in productivity (see Gaines et al.[10] for a detailed justification of this assumption); and (3) biomass, catch, and profits were updated based on a modified version of the Costello et al.[8] bioeconomic model and the selected management scenario. The bioclimatic envelope model projects distributions based on temperature only[9], and may not capture the impacts of deoxygenation, acidification, and other ocean changes that can be non-linearly correlated with temperature. The projected changes in distribution and productivity are qualitatively similar to other marine ecosystem models despite their differing specifications and assumptions[11].

Of the five management scenarios evaluated by Free et al.[2], we consider two here: (1) business-as-usual (a.k.a., “no adaptation”) and (2) climate-adaptive fisheries management (a.k.a., “full adaptation”). Climate-adaptive fisheries management adapts to both climate-driven shifts in productivity and distribution (**Supplementary Tables 5-6**). Productivity shift adaptations improve fisheries management by implementing a dynamic, economically-optimal harvest policy given current biological conditions, which optimally adjusts harvest mortality on the basis of current biomass and is therefore naturally adaptive to climate-driven productivity changes. These adaptations could be achieved through traditional stock assessment and fisheries management or through other governance institutions that align conservation and economic objectives (see Free et al.[2] for more details). Range shift adaptations result from international cooperation that effectively maintains management as stocks shift into new management areas. Business-as-usual fisheries management fails to implement either adaptation (**Supplementary Tables 5-6**): it maintains current (and often suboptimal) harvest rates for species that do not shift spatially, while management degrades to open access for stocks that shift into new management areas.

The Free et al.[2] analysis considers only species-specific stocks described in the FAO Landings Database[12] (i.e., it excludes NEI stocks and stocks with catch reported at the class, order, family, and genus levels) and therefore includes 59% of global fisheries catch. To measure the impact of climate change and fisheries management on the excluded fisheries, we linearly scaled the landings of the included fisheries in the initial year of the projections (2012) to match total reported landings in the FAO Landings Database. This assumes that landings from the excluded (non-species-specific) stocks change in proportion to the effects of climate change and management on the included (species-specific) stocks. We assume that 18% of landings are directed to reduction (i.e., processing of wild fish into fish oil and fishmeal) as reported by Cashion et al.[13]. This proportion is removed from calculations of seafood production and determines the availability of forage fish for mariculture production as described below. Finally, we converted live-weight landings to their edible meat equivalents using conversion factors from Roberts[5] (**Supplementary Table 8**) and calculated global and coastal country-level edible meat *per capita* using population projections from UN-DESA[1].

3. Mariculture analysis

3.1 Overview

We forecast the sustainable mariculture production potential of 123 finfish and 22 bivalve species in 2021-2030, 2051-2060, and 2091-2100 under four climate scenarios (RCPs 2.6, 4.5, 6.0, 8.5; **Supplementary Table 4**) while accounting for the joint constraints of environmental suitability, competing ocean uses, economic feasibility, availability of feed for fed-mariculture, and consumer demand[3] (**Supplementary Tables 1-2**). In each year, we mapped the suitability of a 10 km x 10 km ocean grid for finfish and bivalve mariculture. Finfish habitat suitability was limited by temperature, salinity, and oxygen availability. Bivalve habitat suitability was additionally limited by primary productivity and ocean acidification. Only cells with suitability in every year of each decade-long period were considered environmentally suitable. We excluded environmentally suitable cells with existing uses (i.e., marine protected areas, high density shipping lanes, and oil development) and in waters deeper than 200 m and with wave intensity and current velocity unsuitable for mariculture operations. We calculated the production potential of the remaining suitable cells based on sustainable finfish and bivalve mariculture farm designs and species-specific growth rates and times to and sizes at harvest. We calculated the cost, revenue, and profits of production in each cell and assumed that the cell would be developed for both the most profitable finfish and the most profitable bivalve species. We limited the potential for finfish mariculture on the availability of feed from capture fisheries (which is determined using the capture fisheries scenarios described above). When necessary, we capped production potential based on the estimated upper limits of future consumer demand ("extreme demand" scenario = 2050 demand doubled) for finfish (32/28 million mt of total/meat production) and bivalve (103/18 million mt of total/meat production) mariculture as estimated by Costello et al.[14].

3.2 Data collection

3.2.1 Stock selection

We evaluated the production potential of mariculture species currently under production as indicated in the FAO Aquaculture production data as well as mariculture species considered for production as indicated in the review of Froehlich et al.[15] and subsequently used by Gentry et al.[16] and Froehlich et al.[17] (**Supplementary Fig. 2**). From the FAO Aquaculture Production Database, we identified 196 mariculture species (130 finfish, 66 bivalves) farmed since 2010. Froehlich et al.[15] identified an additional 26 mariculture species (22 finfish, 4 bivalves). We removed ornamental species cultured for the aquarium trade, brackish species not cultured offshore, and bivalve species not cultured on lines (see cost model below). Ultimately, we were able to collect the required life history parameters and environmental tolerances for 144 of these species (122 finfish, 22 bivalves). These species span 12 orders and 36 families (**Supplementary Figs. 3-4**), exhibit varying environmental tolerances (**Supplementary Fig. 5**), and are in various stages of development (**Supplementary Fig. 2**).

3.2.2 Life history traits

Our analysis of mariculture production potential required four sets of life history information: (1) natural mortality rates; (2) Von Bertalanffy growth parameters to estimate the time required for each species to reach harvestable size; (3) length-weight parameters to estimate the weight of each species at harvest; and (4) tolerance of each species to temperature and salinity. We used FishLife[18], a multivariate statistical model trained on FishBase data[19], to estimate average mortality and growth parameters for most finfish species. Missing values were estimated using mean species-level FishBase values (**Supplementary Figs. 3-4)**. We used mean species-, genus-, or family-level SeaLifeBase values[20] for bivalves and replaced genus- and family-level means with values from the literature where possible (**Supplementary Figs. 3-4**). We collected mean species-, genus-, or family-level length-weight parameters for finfish and bivalves using FishBase and SeaLifeBase, respectively (**Supplementary Fig. 4**). We accessed this data using the *rfishbase* package[21]. We used the minimum and maximum values in AquaMaps occurrence data[7] to characterize species temperature and salinity tolerances (**Supplementary Fig. 5**).

3.2.3 Production parameters

Our analysis also required four sets of production parameters: (1) size at harvest; (2) feed conversion ratio (FCR; i.e., kilograms of feed needed to grow a kilogram of fish); (3) proportion of feed composed of fishmeal (FM) and fish oil (FO); and (4) price-at-first-sale (a.k.a., farm-gate price or ex-farm price). We collected information on the median harvest size of 38 finfish and 9 bivalve species from the FAO Cultured Aquatic Species Fact Sheets[22]. We found that finfish and bivalves are generally harvested at 67% and 52% of their asymptotic lengths, respectively, and used these values to calculate species-level harvest sizes (**Supplementary Figs. 6-7**). We assembled time series of group-level (e.g., salmons, milkfish, eels, misc marine fish, etc.) FCRs and feed compositions (FM/FO percentages) from Tacon and Metian[23] and Tacon and Metian[24], respectively (**Supplementary Fig. 8; Supplementary Table 7**). We calculated the current price of each mariculture species as the mean price-at-first-sale (a.k.a., farm-gate price or ex-farm price) over the most recent five years (2013-17) in the FAO Aquaculture production price data. We used the median value for each International Standard Statistical Classification of Aquatic Animals and Plants (ISSCAAP) group on the premise that species within a group are substitutes (**Supplementary Fig. 9**). In summary, harvest sizes are derived from species-level asymptotic lengths but class-level (i.e., finfish and bivalves) harvest size proportions, FCRs and feed compositions are based on feed group-level (e.g., salmons, trouts, oysters, mussels, etc.) projections, and prices are based on ISSCAAP group-level medians.

3.2.4 Climate projections

We projected mariculture potential under four increasingly severe climate change scenarios (RCPs 2.6, 4.5, 6.0, and 8.5; **Supplementary Table 4**) using output from the GFDL-ESM2G earth system model[25,26]. The GFDL-ESM2G model provides monthly gridded output with a resolution of 1 degree longitude and 0.375-0.5 degree latitude (lower resolution at the poles). We used sea surface temperature, salinity, and dissolved oxygen concentration to constrain the suitability of finfish mariculture and total chlorophyll concentration and aragonite saturation to additionally constrain the suitability of bivalve mariculture (**Supplementary Table 9**). We also excluded areas with current speeds and wave intensities that are unsuitable for mariculture technology (**Supplementary Table 9**). Aragonite saturation is not an output of the GFDL-ESM2G model and was derived using the *seacarb* R package[27] and the following outputs from the GFDL-ESM2G model: sea surface temperature, salinity, silicate concentration, phosphate concentration, total alkalinity, and dissolved inorganic concentration (**Supplementary Table 10; Supplementary Fig. 11**). Because the *seacarb* package requires molecular concentrations in moles per kg rather than the moles per m^3 (i.e., the units used in the GFDL-ESM2G model output), we converted the GFDL-ESM2G concentrations using the density of seawater output. Wave intensity is also not an output of the GFDL-ESM2G model so we used projections of significant wave heights under RCPs 2.6, 4.5, and 8.5 generated by Song et al.[28] (**Supplementary Table 11**). Significant wave height is the average wave height, from trough to crest, of the highest one-third of the waves. For all of these climate variables, we calculated annual minimums, maximums, and averages and reprojected them to match the 10 km x 10 km grid used throughout the analysis. Although our projections of mariculture production potential would vary based on choice of earth system model, our use of the GFDL-ESM2G, which is one of the “warmer” earth system models[29], and our finding that mariculture production is considerably more limited by feed availability and consumer demand than by habitat suitability collectively suggests that our results are likely robust to choice of earth system model.

3.3 Estimating production potential

3.3.1 Identifying suitable areas

We mapped habitat suitability for the production of each mariculture species on a 10 km x 10 km ocean grid assuming that habitat suitability for finfish species is limited by temperature, salinity, and oxygen availability and that habitat suitability for bivalve species is additionally limited by primary productivity and ocean acidification (**Supplementary Table 9**). We assumed that mariculture species can only be cultivated in areas with annual minimum and maximum temperatures inside their species-specific temperature tolerances and annual average salinities inside their species-specific salinity tolerances (**Supplementary Fig. 5**). We followed the specifications of Gentry et al.[16] and assumed that finfish and bivalve species can only be cultivated in areas with annual average dissolved oxygen concentrations greater than 4.41 mg/L (0.28 mol/m^3) and 1.99 mg/L (0.12 mol/m^3), respectively. See the original references for detailed derivations and justifications of these environmental limits. We assumed that bivalve mariculture can only occur in areas with high and stable primary productivity which we identified as areas with annual total chlorophyll concentrations meeting the following condition: the annual mean minus the annual standard deviation is greater than 0.2 mg/m^3. This value was manually selected to match the map of current suitability for bivalve mariculture of Gentry et al.[16] and Froehlich et al.[17] (**Supplementary Fig. 10**). We assumed that bivalve species can only be cultivated in areas with average annual aragonite saturation (Ω) greater than 1.75. This threshold is slightly higher than the “break-even” point (Ω=1.70) for viable commercial mariculture for Pacifc oysters (*Crassostrea gigas*) at a shellfish hatchery in Washington, U.S.A.[30]. We assumed that economic and technological constraints prevent the development of either finfish or bivalve mariculture in waters deeper than 200 m, with annual maximum wave heights less than 5 m, and with annual maximum current speeds less than 1.0 m/s[31]. We assumed that mariculture will only occur in areas with annual average current speeds greater than 0.04 m/s to minimize negative environmental impacts from finfish mariculture and to ensure sufficient flow for bivalve mariculture[31]. We assumed that mariculture will only occur in undisputed exclusive economic zones (EEZs) due to the high social uncertainty of establishing farms in international or disputed waters (**Supplementary Fig. 12**). We also excluded EEZs surrounding uninhabited or sparsely inhabited islands (e.g., Clipperton, Heard/McDonald Islands, Pitcairn, Wake Islands) (**Supplementary Table 12; Supplementary Fig. 12**) and areas currently being used as marine protected areas (MPAs), high density shipping lanes, or offshore oil development (**Supplementary Fig. 13**).

3.3.2 Estimating biological production potential

We calculated production potential in each suitable cell based on sustainable farm designs (**Supplementary Table 13; Supplementary Fig. 14**), sizes at harvest, and the time required to reach harvest sizes. Each square kilometer of finfish farm was assumed to contain 20 x 9,000-m^3 cages (**Supplementary Table 14**) stocked with the species-specific number of juveniles required to attain 15 kg/m^3 of fish at the time of harvest after accounting for natural mortality. This harvest density is the European organic standard for sustainable mariculture[32]. For bivalve mariculture, we conservatively assume a maximum harvest density of 1500 mt/km^2, which is approximately half the density used by U.S. shellfish growers[33]. We calculated the species-specific number of juveniles required to attain this density, after accounting for natural mortality, and the species-specific number of longlines required to culture these individuals assuming that longlines are 120-m long and have 2,109 ft of fuzzy rope[33] and a density of 400 cm of bivalves per foot of rope at the time of harvest[16]. We calculated (all species-specific) the number of juveniles (N_o) required to achieve the target number of adults (N_t) using natural mortality (M) and time to harvest (t) in the following equation:

$$N_o = \frac{N_t}{e^{-Mt}} \quad \text{Eq. 1}$$

We calculated the weight at harvest (W_s, g) from length at harvest (L_s, cm) for species s using species-specific allometric parameters and the length-to-weight equation:

$$W_s = a_s {L_s}^{b_s} \quad \text{Eq. 2}$$

We calculated the time required for species s to reach its harvest size (T_s, yr) using the rearranged Von Bertalanffy growth equation and species-specific growth parameters:

$$T_s = -log(1 - L_s/L_{inf,s})/K_s \quad \text{Eq. 3}$$

The annual production potential (P_s, g/yr) of species s in one of its 10 km x 10km suitable cells (which each contain 100 1-km^2 farms) can therefore be calculated as:

$$P_s = \frac{N_s * W_s}{T_s} * 100\ farms \quad \text{Eq. 4}$$

where N_s is the number of stocked juveniles. This value is converted to metric tons per year. **Supplementary Fig. 15** shows the distribution of annual production potential by ISSCAAP group.

3.3.3 Constraining production potential by economic feasibility

We assumed that mariculture will only occur where it is profitable (i.e., profits greater than zero). We calculated the annual profitability of a cell as the annual revenues minus the annual costs. The annual revenue (USD/yr) of a cell developed for species *s* is the product of the productivity of the cell (mt/yr) and the price of species *s* (USD/mt). The annual cost of developing that cell for species *s* was calculated as the sum of the amortized capital costs of purchasing vessels and equipment (i.e., cages, lines, and feed gear) and the annual operating costs associated with labor, fuel, feed, insurance, and vessel and equipment maintenance (**Supplementary Tables 15-17**). We amortized capital costs assuming a 10% discount rate and 10-year payoff period. We calculated labor costs assuming that each 1 km^2 farm employs 8 workers who are compensated for a 40 hour week plus transit time[33]. Workers were compensated using country-level median wages from the World Bank[34] (**Supplementary Figs. 16-17**). We calculated fuel costs based on the mariculture vessel specifications (e.g., number, speed, and efficiency of vessels) of Lester et al.[33], the distance of the farm from shore, and country-level median diesel costs from the World Bank[35] (**Supplementary Figs. 16-17**). We acquired the World Bank development indicators using the *wbstats* R package[36]. We calculated the cost of annual feed demand as the product of the productivity of the cell (mt/yr), the feed conversion rate (FCR; mt of feed / mt of production), and the price of feed (USD/mt). The cost of vessels, equipment, vessel and equipment maintenance, insurance, and other annual operating costs were based on Lester et al.[33] and Rubino[37]. See **Supplementary Tables 15-17** for cost parameters and sources.

3.3.4 Constraining by feed availability

The potential for fed-mariculture is limited by the availability of feed ingredients derived from wild capture fisheries[38] but this limitation could be reduced through four advances (**Supplementary Table 18**). First, the amount of raw material available for reduction could be increased by (a) reforming fisheries management to increase landings; (b) processing more capture species or landings for reduction; or (c) processing a larger proportion of capture landings or aquaculture production for by-products (a.k.a., trimmings or waste; i.e., the offal or skeletons, skin, and guts of fish)[39]. Second, the proportion of total fishmeal and fish oil production used by mariculture could be increased by reducing or eliminating the use of fish ingredients in feed for non-carnivorous freshwater aquaculture and non-carnivorous terrestrial agriculture. Third, the replacement of fish ingredients with alternative sources of nutrition would reduce the “Fish In, Fish Out” (FIFO) ratio of mariculture by reducing the amount of wild fish required to produce farmed fish. At the extreme, the elimination of fish ingredients from fish feed would entirely decouple the reliance of fed-mariculture on capture fisheries. Finally, technological advances that increase the efficiency by which feed is converted into farmed fish (i.e., decrease in the feed conversion rate) would reduce the FIFO ratio by increasing the amount of farmed fish produced from a unit of wild fish[40].

We evaluated the potential for fed-finfish mariculture under two cross-sector (fisheries and mariculture) policy scenarios that affect feed availability and conversion efficiency: (1) a "business-as-usual" (BAU) scenario which assumes BAU fisheries management (**Figs. 1a & Supplementary Fig. 18**) and moderate advances in feed technology (FIFO ratios projected for 2030, 0.01-0.91; **Fig. 2d & Supplementary Fig. 19**) and (2) a "progressive reforms" scenario which assumes climate-adaptive fisheries management (**Fig. 1a & Supplementary Fig. 18**) and progressive advances in feed technology (FIFO ratios projected for 2050, 0.001-0.30; **Fig. 2d & Supplementary Fig. 19**). We projected future FIFO ratios assuming continued exponential decline in the FIFO ratios reconstructed through analysis of trends in feed conversion rates (FCRs)[23] and feed compositions (FM/FO percentages)[24] (**Supplementary Figs. 8 & 19**). See Equation 5 below for the derivation of FIFOs from FCRs and feed compositions. In both scenarios, we assume that all finfish production is fed given current trends in the use of feed in finfish mariculture[23] (**Supplementary Fig. 8**). We also assume no change in the (1) proportion of global landings used for reduction (i.e., processing of wild fish into fishmeal and fish oil) (18% today[13]) or (2) proportion of reduction-destined landings directed to mariculture feed (21% today[38]).

As ocean cells are developed for finfish mariculture, the global supply of forage fish available for mariculture feed is incrementally depleted. The forage fish demand ($FF_{p,s}$, mt) of patch *p* for species *s* is calculated as the mariculture production potential ($AQ_{p,s}$, mt) of patch *p* for species *s* multiplied by the "Fish In, Fish Out" ratio ($FIFO_s$) for species *s*:

$$FF_{p,s} = AQ_{p,s} * FIFO_s \quad \text{Eq. 5}$$

where the FIFO ratio is derived for each feed group in each feed scenario using the following equation from Jackson[41]:

$$FIFO = FCR \times \frac{Level\ of\ FM\ in\ feed + Level\ of\ FO\ in\ feed}{Yield\ of\ FM\ from\ forage\ fish + Yield\ of\ FO\ from\ forage\ fish} \quad \text{Eq. 6}$$

where the feed conversion rate (FCR) and percent of fishmeal (FM) and fish oil (FO) in feed vary based on feed group and technology scenario (**Supplementary Table 7; Supplementary Figs. 8 & 19**) and the yields of fishmeal and fish oil from forage fish are fixed at 22.4% and 4.85%, respectively[39]. The development of additional cells for finfish mariculture is halted once the forage fish supply for a given feed scenario, climate scenario, and decade is depleted (**Supplementary Fig. 18**).

We evaluated four development patterns that dictate the distribution of mariculture production among coastal countries: (1) current development; (2) proportional development; (3) offset-based development; and (4) optimum development. The current development pattern assumes that future production occurs in proportion to current mariculture production (**Supplementary Fig. 20**). In this scenario, only countries with mariculture today can have mariculture in the future. The proportional development pattern assumes that future production will be proportional to projected 2100 population size. In this scenario, all countries can have mariculture in the future. The offset-based development pattern assumes that future production will only occur in countries expected to lose *per capita* seafood supplies from capture fisheries. In this scenario, countries gaining *per capita* seafood supplies fisheries would not have mariculture in the future. Finally, in the optimum development scenario, mariculture development is optimized to maintain seafood production per capita for the maximum number of countries. In all four scenarios, countries utilize their production allocation by developing the most profitable cells first.

3.3.5 Inspecting ecosystem-wide sustainability of bivalve mariculture

We evaluated the sustainability of bivalve mariculture that would result from each of the four development patterns by calculating the density of cultured bivalves in each of the 232 Marine Ecoregions of the World[42] (MEOWs) projected for each period (i.e., 2021-2030, 2051-2060, and 2091-2100) and comparing this density to an ecosystem-level carrying capacity for cultured bivalves. We derived the ecosystem-level carrying capacity using the review of Smaal and van Duren[43] who define two ecological indices of bivalve carrying capacity and report these indicators for 19 large marine ecosystems from around the world. We calculated the mean density of cultured bivalves in the 8 ecosystems identified by Smaal and van Duren[43] as exhibiting low impact clearance ratios (i.e., time required for bivalves to filter a water body relative to the time required for the water body to renew itself) and high availability of food for bivalves (**Supplementary Fig. 21**). Smaal and van Duren[43] report cultured bivalve densities in ash-free dry weights. We converted these densities to their live-weight equivalents using conversion factors from Ricciardi and Bourget[44]. We found an ecosystem-wide density of 57.9 mt/km^2 to be the carrying capacity for cultured bivalves. This value was rarely exceeded for any of the MEOWs under any of the development scenarios in any of the evaluated periods (**Supplementary Fig. 22**) and could be avoided with the effective planning described in the main text.

3.3.6 Sensitivity analysis

We evaluated the sensitivity of our results to alternative projections of human population size and to a scenario in which prices were 30% lower and costs were 30% higher than predicted by the model. Prices may be lower due to increased seafood supply[45] and costs may be higher due to uncertainty in the cost model or to climate change impacts not directly accounted for in our model (e.g., storms, disease, harmful algal blooms).

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Supplementary Tables and Figures

Supplementary Tables

Supplementary Table 1. Differences in approaches for modeling mariculture production potential in the present study and three similar analyses[1].

Parameter	Gentry et al. (2017) Biological potential today	Froehlich et al. (2018) Biological potential under CC	Costello et al. (2020) Economic potential today	Present study Economic potential under CC
Model specifications				
Number of species	180 (120 finfish, 60 bivalves)	180 (120 finfish, 60 bivalves)	180 (120 finfish, 60 bivalves)	144 (122 finfish, 22 bivalves)
Spatial resolution	0.042 degree	1.0 degree	0.042 degree	10 km
Temporal resolution	Today	1 historic and 4 future periods	Today	2021-2030, 2051-2060, 2091-2100
Production parameters				
Harvest size	35 cm finfish, 4 cm bivalves	35 cm finfish, 4 cm bivalves	35 cm finfish, 4 cm bivalves	Species-specific
Time-to-harvest	Species-average	Species-average	Species-average	Species-specific
Length-weight params.	1 for finfish, none for bivalves	1 for finfish, none for bivalves	1 for finfish, 1 for bivalves	Species-specific
Constraints				
Human use	EEZs, minus MPAs/shipping/oil	EEZs	EEZs, minus MPAs/shipping/oil/depth	EEZs, minus MPAs/shipping/oil/depth
Environmental	SST, DO, chlorophyll (bivalves)	SST, chlorophyll/acidification (bivalves)	SST, DO, chlorophyll (bivalves)	SST, DO, CHL/acidification (bivalves)
Operational	Depth	Not included	Depth	Depth, current velocity, wave intensity
Climate change	Not included	RCP 8.5	Not included	RCPs 2.6, 4.5, 6.0, and 8.5
Economic feasibility	Not included	Not included	Multiple prices (supply curve)	Current price per species
Feed availability	Not included	Not included	Multiple scenarios	Multiple scenarios
% FM/FO in feed	---	---	Single value (Atlantic salmon)	Group-specific values
Feed conversion rate	---	---	Single value (Atlantic salmon)	Group-specific values

[1] Abbreviations: CC = climate change; EEZ = exclusive economic zone; SST = sea surface temperature; DO = dissolved oxygen; CHL = chlorophyll; SAL = salinity.

Supplementary Table 2. Actions taken to explicitly account for the constraints on mariculture expansion outlined by Troell et al.[3] in their response to Gentry et al.[16].

	Troell et al. (2017) concern	How we explicitly address this concern
1	Bivalve mariculture "will probably compete for the same resource base (plankton and organic matter) that capture fisheries and overall ecosystem structure depend on. The extent of this hypothetical side-effect of large-scale open water mussel farming is uncertain, but as fisheries contribute substantially to food security, especially in many low-income countries, it may need to be considered for the large-scale instalments that Gentry and colleagues anticipate."	We explicitly model sustainable bivalve mariculture with minimal impacts on marine ecosystems and wild fisheries by employing precautionary stocking densities equivalent to half of California's (USA) guidelines. Furthermore, we derive an ecosystem-wide carrying capacity for cultured bivalves using the review and carrying capacity indices of Smaal and van Duren (2019) and find that few of the 232 Marine Ecoregions of the World (MEOWs) would exhibit cultured bivalve densities above this carrying capacity in any of the evaluated mariculture development scenarios. The rare instances in which bivalve density exceeded these thresholds could be avoided through effective planning and coordination.
2	"Feed development will ultimately constrain whether any fed aquaculture can expand sustainably in the future. Including this factor as a superimposed layer in Gentry and colleagues' sea-space model would reveal that feed availability and feed costs will prevent further expansions of mariculture long before any ocean space limitations are reached."	We explicitly account for feed limitations in scenarios with different levels of (1) feed availability as a result of fisheries management (business-as-usual and climate-adaptive management); (2) feed conversion efficiency as a result of technological innovations (moderate and substantial technological advances); and (3) feed distribution as a result of mariculture development patterns (current, proportion, offset-based, and optimum development patterns).
3	"Gentry et al. join others in pointing out that capital and operating costs can be high for offshore aquaculture. These costs influence species choice and may also affect who will have access to the products of ocean aquaculture."	We explicitly calculate the cost of mariculture production (i.e., upfront capital costs of vessels and equipment and annual operating costs of maintenance, wages, fuel, feed, and insurance) in every evaluated grid cell and assume that mariculture will only occur in profitable areas.

Supplementary Table 3. Assumptions and uncertainties in the mariculture analysis and their potential impact on our results. The "Most Likely?" column indicates our speculation about the most likely implication of the assumption or uncertainty (???? = unknown; ----- = neutral).

Decision point	Explanation of the assumption or uncertainty	Mechanisms for the assumption to: Underestimate production	Overestimate production	Most likely?
Modelled factors				
Species selection				
No brackish species	We excluded brackish species to (1) make it clear that no freshwater species were included in the analysis and (2) to avoid inclusion of species cultured in tanks or saltwater ponds.	This assumption can only underestimate mariculture production potential as some of these species could potentially be grown offshore.		Underestimate
No bivalves cultured on longlines	We excluded bivalve species such as clams, cockles, and scallops that are not commonly grown on lines given the parameterization of our cost model.	This assumption can only underestimate mariculture production potential as some of these species could potentially be grown offshore.		Underestimate
All other species currently cultured	We included all other mariculture species, including species in early stages of development and including species being considered from development.		This assumption can only overestimate mariculture production potential as some of these species may not be as viable for production as the model expects.	Overestimate
Life history traits				
Growth rate	We used the median growth rate, as observed in the wild, in all locations.	This assumption is likely to underestimate mariculture production potential as growth rates are likely to be higher on farms than in the wild due to effective husbandry.	However, if site selection occurred only in the fringes of a species environmental niche, then growth rates could be lower than the wild average. This seems less likely.	Underestimate
Mortality rate	We used the median mortality rate, as observed in the wild, in all locations.	This assumption may underestimate mariculture production potential as mortality rates may be lower on farms in the wild due to husbandry and the requirement of high survival for profitable mariculture.	However, differences between mortality on farms and in the wild are smaller than differences in growth rate, due to disease, crowding, and abrasion.	Weak underestimate
Environmental tolerance	We used the niche breadth across the native range of a species in the wild to determine environmental suitability.	This could be an accurate assumption given that (1) husbandry and selective breeding could maintain high productivity at the fringe of environmental niches and (2) tolerance is likely wider than observations owing to	This could weakly overestimate mariculture production potential if productivity is significantly lower at the fringe of the range.	????

		sampling sparsity and other factors (e.g., competition) determining range limits.		
Harvest parameters				
Harvest size	We assume that size at harvest is a proportion of the asymptotic size based on a meta-analysis.	This parameter is unlikely to strongly impact estimates of production potential since its likely an unbiased estimator of harvest size.		----
Time to harvest	We calculate time to harvest based on the derived harvest size and the median growth rate.	This assumption is likely to underestimate mariculture production potential as growth rates are likely to be higher on farms than in the wild due to effective husbandry, which means the time to harvest would be shorter than predicted by the model.		Underestimate
Climate change				
ESM choice	We used the GFDL-ESM2G ESM.	This model is "warmer" than other global ESMs and may therefore be more pessimistic about future warming and its impacts on mariculture production potential.		Underestimate
RCP choice	We evaluated all four RCPs.	This thorough evaluation makes our results robust to choice of RCP scenario.		----
ESM certainty	The GFDL-ESM2G ESM projections are inherently uncertain.	However, we evaluate all four RCPs so this captures mariculture potential under four potential and contrasting futures, which is still highly useful.		----
ESM resolution	The resolution of the GFDL-ESM2G ESM projections implies that the environmental values are constant throughout the whole cell.	This is an oversimplification but since the values are unbiased they should not significantly impact the results.		----
Farm design				
Finfish farm design	Our farms are inspired by precautionary interpretations of farm designs in the highly regulated USA. The stocking density is equivalent to the European organic standard.	This assumption may weakly underestimate finfish mariculture production potential but is justified given our developing knowledge of the impacts of mariculture on the environment.	Both assumptions would overestimate mariculture production potential if they led to ecosystem degradation when mariculture scales to the production levels predicted by the analysis. We think this is unlikely given the level of precaution and the post-hoc analyses on bivalves.	Weak underestimate
Bivalve farm design	Our farms are inspired by precautionary interpretations of farm designs in the highly regulated USA. The stocking density is half the U.S. standard and post-hoc analyses reveal that cultured densities are sufficiently low at the ecoregion scale.	This assumption is more likely to underestimate bivalve mariculture production potential due to the highly precautionary limit on bivalve density.		Underestimate
Feed assumptions				

FIFO rates	We assume exponential decline in FIFO rates consistent with the last 20 years in our technology scenarios.		Although industry could outperform these projections, progress may slow as maintaining the nutritional content and price of feed becomes challenging with lower FIFOs. We only projected to 2050 (and apply it to 2100) to account for this.	Overestimate
Proportion landings to reduction	We assume that the proportion of landings dedicated to reduction will remain constant.	It is difficult to predict this behavior and the proportion of fisheries landings reduced to FM/FO could go up or down.		????
Proportion of FM/FO to mariculture	We assume that the proportion of FM/FO production dedicated to mariculture will remain constant.	It is difficult to predict this behavior and the proportion of FM/FO dedicated to aquaculture could go up or down.		????
Costs				
Prices	We assume today's prices in our base model results (30% lower in the sensitivity analysis).		This may overestimate production potential as prices are expected to fall with increased production potential. However, we found our results to be insensitive to decreases in price of 30%.	Overestimate
Costs	We assume current country-specific prices for fuel/wages and current U.S. costs for other capital and operational costs.	The parameterization based on the U.S. may overestimate costs and underestimate production potential.	We conducted a sensitivity analysis to confirm that our results are insensitive to a scenario in which the model underestimates costs by 30% (and prices are also 30% lower).	Underestimate
Unmodeled factors				
Climate change				
Storms, pathogens, and HABs	Storms, pathogens, and harmful algal blooms may increase under climate change and are not explicitly accounted for here.		The exclusion of these constraints could overestimate mariculture production potential. However, we employ precautionary constraints to limit the effect of these stressors, model costs of insurance, and examine sensitivity of our result to underestimating costs.	Overestimate
Technological advances				
IMTA	We model mariculture as monocultures and do not model IMTA.	IMTA could increase the productivity of farms while also reducing costs, environmental		Underestimate

		impacts, and vulnerability to climate stressors.		
Selective breeding	We do not model the impacts of selective breeding for growth, disease resistance, or environmental tolerance.	Selective breeding could increase the productivity of mariculture and robustness to climate change. However, it would also increase costs.		Underestimate

Supplementary Table 4. Representative Concentration Pathway (RCP) climate change scenarios evaluated in the analysis[46]. The mariculture projections use only the GFDL-ESM2G earth system model while the Free et al.[2] fisheries analysis ensembles results from the earth system models (ESMs) listed below (see Gaines et al.[10] and García Molinos et al.[9] for details).

Scenario	Projected warming (°C)*	Description**	ESMs ensembled for the Free et al. (2020) fisheries analysis
RCP 2.6	1.0 (0.3-1.7)	Peak in radiative forcing at ~3.0 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline to 2.6 W/m^2 by 2100	bcc-csm1-1, bcc-csm1-1-m, CanESM2, CCSM4, CESM1-CAM5, CNRM-CM5, CSIRO-Mk3-6-0, EC-EARTH, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-H, GISS-E2-H, GISS-E2-R, GISS-E2-R, GISS- E2-R, HadGEM2-AO, HadGEM2-ES, IPSL-CM5A-LR, IPSL-CM5A-MR, MIROC5, MPI-ESM-LR, MPI-ESM-MR
RCP 4.5	1.8 (1.1-2.6)	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO^2 eq) at stabilization after 2100	ACCESS1-0, ACCESS1-3, bcc-csm1-1, bcc-csm1-1-m, CanESM2, CCSM4, CESM1-BGC, CESM1-CAM5, CMCC-CM, CMCC-CMS, CNRM-CM5, CSIRO- Mk3-6-0, EC-EARTH, FIO-ESM, GFDL-CM3, GFD
RCP 6.0	2.2 (1.4-3.1)	Stabilization without overshoot pathway to 6.0 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100	bcc-csm1-1-m, CCSM4, CESM1-CAM5, CSIRO-Mk3-6-0, FIO-ESM, GFDL- CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-H, GISS-E2-H, GISS-E2-R, GISS-E2-R, GISS-E2-R, HadGEM2-AO, HadGEM2-ES, IPSL- CM5A-LR, MIROC5, MRI-CGCM3, NorESM1-M, NorESM1-ME
RCP 8.5	3.7 (2.6-4.8)	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100	ACCESS1-0, ACCESS1-3, bcc-csm1-1, CanESM2, CCSM4, CESM1-BGC, CESM1-CAM5, CMCC-CM, CMCC-CMS, CNRM-CM5, CSIRO-Mk3-6-0, EC-EARTH, FIO-ESM, GFDL-CM3, GFDL-ESM2G, GFDL-ESM2M, GISS-E2-H, GISS-E2-H, GISS-E2-H, GISS-E2-R, GISS-E2-R, GISS-E2-R, HadGEM2-CC, HadGEM2-ES, inmcm4, IPSL-CM5A-LR, IPSL-CM5A-MR, IPSL-CM5B-LR, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3, NorESM1-M, NorESM1-ME

Supplementary Table 5. Fisheries management scenarios evaluated in the analysis (HCR=harvest control rule; EEZ=exclusive economic zone).

Fisheries management scenario
Business-as-usual (a.k.a., no adaptation)
This scenario assumes that no action is taken. The HCR for Static species-stocks remains at Current Fishing Mortality Rate, and the Gradual Shift: Current Fishing Morality Rate to Open Access policy is applied to Transboundary species-stocks, as a lack of transboundary agreements leads to Open Access in Transboundary species- stocks.
HCR for static stocks: Current fishing mortality
HCR for transboundary stocks: Gradual shift: current fishing mortality to open access
Climate-adaptive (a.k.a., full adaptation)
Full Adaptation assumes that management adapts to the anticipated changes to productivity and effectively prepares for spatial shifts due to climate change. Here, we assume that 1) the naturally adaptive HCR (Economically Optimal), and 2) strong, flexible transboundary institutions that lead to the successful management of all stocks even as they shift into and out of EEZs are adopted. In this scenario, all stocks are managed under the Economically Optimal HCR.
HCR for both static and transboundary stocks: Economically optimal

Supplementary Table 6. Harvest control rules used in the management scenarios.[1]

Harvest control rule (HCR)
Current fishing mortality
This HCR continues the initial fishing mortality rate (i.e., F in 2012) through all years.
Economically optimal fishing mortality
This HCR achieves maximum net present value (NPV) over an infinite time horizon under the current climate and biological conditions. Each stock has its own optimized harvest policy where fishing mortality rate is a function of biomass. This HCR is determined using a dynamic optimization routine for each stock.
Gradual shift from current to open access fishing mortality
This HCR is only relevant to transboundary stocks. For these stocks, fishing mortality begins at the initial fishing mortality rate (i.e., F in 2012), then changes at a constant rate towards open access fishing mortality (i.e., fishing mortality that achieves open access equilibrium at 30% of B_{MSY}), which is reached in the year in which the first spatial shift into or completely out of an EEZ occurs. Fishing mortality remains at the open access rate for all subsequent years.

[1] See the Gaines et al.[10] supplementary information for more details on the management scenarios and harvest control rules.

Supplementary Table 7. Feed parameters by feed group (FIFO = "fish in, fish out").[1]

	2020 values:				Projected values:	
Feed group	**Feed conversion rate (FCR)**	**Percentage of fishmeal in feed**	**Percentage of fish oil in feed**	**FIFO ratio**	**2030 FIFO ratio**	**2050 FIFO ratio**
Eel	1.5	25%	2%	1.49	0.910	0.304
Milkfish	1.5	1%	0.50%	0.09	0.030	0.003
Misc freshwater fish	1.7	15%	2%	1.06	0.686	0.194
Misc marine fish	1.5	8%	3%	0.65	0.310	0.052
Salmon	1.3	8%	6%	0.67	0.296	0.057
Tilapia	1.6	1%	0%	0.06	0.014	0.001
Trout	1.3	8%	4%	0.57	0.266	0.053

[1] See **Figure S23** for FIFO projections.

Supplementary Table 8. Live-weight to edible meat conversion factors from Roberts[5].

Group	Conversion factor	Source
Finfish	0.87	Edwards et al. 2019
Cephalopods	0.69	FAO 1989
Crustaceans	0.36	Edwards et al. 2019
Echinoderms	0.30	Costello et al. 2020
Molluscs	0.17	Edwards et al. 2019

Supplementary Table 9. Environmental variables and tolerance limits used to map the suitability of ocean cells for finfish or bivalve mariculture.

Code (native units)	Variable (converted units)	Finfish limits	Bivalves limits	Limit reference
tos (K)	Sea surface temperature (°C)	species-specific	species-specific	AquaMaps
so (psu)	Sea surface salinity (psu)	species-specific	species-specific	AquaMaps
o2 (mol/m^3)	Dissolved oxygen concentration (mol/m^3)	< 0.2757 mol/m^3 (< 4.41 mg/L)	< 0.1244 mol/m^3 (< 1.99 mg/L)	Gentry et al. (2017)
chl (kg/m^3)	Total chlorophyll concentration (mg/m^3)	not limiting	Mean minus s.d. < 0.2 mg/m3	Derived in this study
-----	Aragonite saturation (Ω, ratio)	not limiting	< 1.75	Barton et al. (2015)
uo / vo (m/s)	Current speed (m/s)	0.04 - 1.0 m/s	0.04 - 1.0 m/s	Froehlich et al. (2017)
Hs (m)	Significant wave height (m)	< 5 m	< 5 m	Froehlich et al. (2017)

[1] Names and units of the environmental variables provided by CMIP5 earth system models, including the GDFL-ESM2G model used in this analysis.
[2] All variables reflect values at the ocean surface.
[3] Derived from the x (uo) and y (vo) velocity components.
[4] From Song et al.[28]

Supplementary Table 10. Environmental variables used to calculate aragonite saturation (Ω) using the *seacarb* R package[27].

Code (native units)	Variable (converted units)
tos (K)	Temperature (°C)
so (psu)	Salinity (psu)
-----	Atmospheric pressure (set to 1 atm)
-----	Hydrostatic pressure (set to 0 bar)
po4 (mol/m3)	Total phosphate concentration (mol/kg)
si (mol/m3)	Total silicate concentration (mol/kg)
-----	Any two of the following:
talk (mol/m3)	Alkalinity (mol/kg)
dissic (mol/m3)	Dissolved inorganic carbon concentration (mol/kg)
-----	Not used: pH, CO2, HCO3, CO3, pCO2
rhopoto (kg/m3)	Density (kg/m3) - used to convert mol/m3 to mol/kg

[1] Names and units of the environmental variables provided by CMIP5 earth system models, including the GDFL-ESM2G model used in this analysis.
[2] All variables reflect values at the ocean surface.

Supplementary Table 11. Projections of significant wave height from Song et al.[28]

Climate scenario	Wave height scenario	Details
RCP 2.6	SSP1-2.6	The low end of the range of future forcing pathways, in which the radiative forcing reaches 2.6 W/m2 by 2100
RCP 4.5	SSP2–4.5	The medium part of the range of future forcing pathways, in which the radiative forcing reaches 4.5 W/m2 by 2100
RCP 6.0*	SSP5-8.5	The high end of the range of future forcing pathways, in which the radiative forcing reaches 8.5 W/m2 by 2100
RCP 8.5	SSP5-8.5	The high end of the range of future forcing pathways, in which the radiative forcing reaches 8.5 W/m2 by 2100

* Song et al.[28] did not evaluate SSP4-6.0 in their analysis so we precautionarily borrow projections from the more severe SSP5-8.5 for this climate scenario.

Supplementary Table 12. Exclusive economic zones (EEZs) excluded from analysis because they surround uninhabited or sparsely inhabited islands.

Sovereign nation	Territory
Antarctica	Antarctica
Australia	Cocos Islands
Australia	Heard and McDonald Islands
Australia	Macquarie Island
Brazil	Trindade
Chile	Islas San Felix and San Ambrosio
Colombia	Bajo Nuevo Bank
Colombia	Quitasueno Bank
Colombia	Serranilla Bank
France	Amsterdam and Saint Paul Islands
France	Clipperton Island
France	Crozet Islands
France	Europa Island
France	Juan de Nova Island
France	Kerguelen
Kiribati	Phoenix Group
Norway	Bouvet
Norway	Jan Mayen
South Africa	Prince Edward Islands
United Kingdom	Ascension
United Kingdom	Pitcairn
United Kingdom	Tristan da Cunha
United States	Howland and Baker islands
United States	Jarvis Island
United States	Johnston Atoll
United States	Palmyra Atoll
United States	Wake Island

Supplementary Table 13. Sustainable finfish and bivalve farm specifications from Gentry et al[16] but modified to be more conservative for bivalve mariculture.

Parameter	Value
Finfish farm (1 sq. km)	
Specifications	
Number of cages	20
Cage volume (m^3)	9,000
Harvest density (kg/m^3) - L_{inf} < 140 cm	15
Harvest density (kg/m^3) - L_{inf} ≥ 140 cm	5
Example farm: Atlantic salmon	
Length at harvest (cm)	70.6
Weight at harvest (kg)	3.7
Time to harvest (yr)	2.6
Natural mortality (1/yr)	0.77
Number of juveniles stocked	5,335,012
Number of adults harvested	740,236
Annual production (mt)	1,048
Annual revenues (USD) @ US$7,836/mt	8,215,040
Bivalve farm (1 sq. km)	
Specifications	
Longline length (m)	120
Fuzzy rope per longline (ft)	2,109
Harvest rope density (cm/foot)	400
Harvest density (mt/sqkm)	1,500
Example farm: Blue mussel	
Length at harvest (cm)	5.9
Weight at harvest (g)	19.1
Time to harvest (yr)	3.4
Number of longlines needed	549
Total number stocked	78,617,591
Annual production (mt)	446.6
Annual revenues (USD) @ US$2,718/mt	1,213,983

Supplementary Table 14. Number of cages per farm documented in a brief literature review.

Farm type	Farm design	Reference
Norway salmon	20-24 pens per farm	FAO (2020)
Canada salmon	10-30 pens per farm	Fraser Riverkeeper (2020)
General salmon farm	12 pen rows	Liu et al. (2016)
General salmon farm	12-36 pens per farm	Stigebrandt et al. (2004)

Supplementary Table 15. Cost parameters common to both bivalve and finfish mariculture.

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 Indicators
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 Indicators
Trip distance (km)	based on farm location		

Supplementary Table 16. Cost parameters for finfish mariculture from Rubino[37].

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$/farm	0	10,000
annual	feed[4]	US$/kg	2	
Plans				
annual	insurance[5]	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$/farm	0	1615.2
Other costs				
annual	on shore cost[6]	US$/year	150,000	250,000

[1] Includes feeder and other equipment
[2] Includes fuel, utilities, diving, repair, etc.
[3] From Thomas et al.[47]
[4] Insurance covers fish and other capital
[5] Includes salaries for 1 manager and 2 office staff

Supplementary Table 17. Cost parameters for bivalve mariculture from Rubino[37].

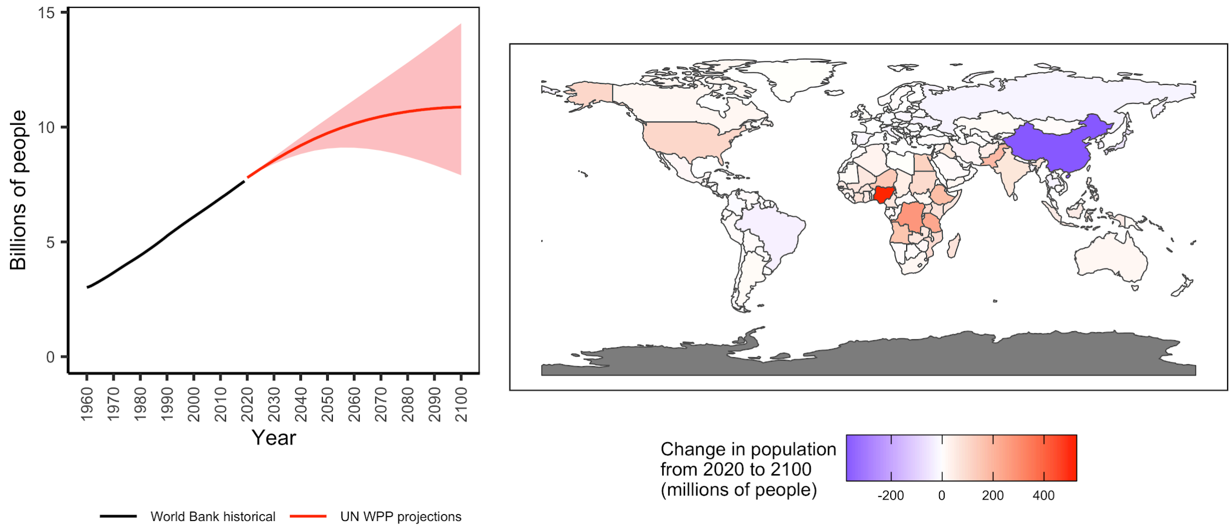
Type	Description	Units	Baseline value (used vessel)	High-end value (new vessel)
Equipment costs				
capital	longline equipment and installation[1]	US$/longline	10,000	
annual	expendable supplies[2]	US$/longline/year	1,700	
Vessel costs				
capital	vessel (+cost of upgrades to used vessels[3])	US$/vessel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

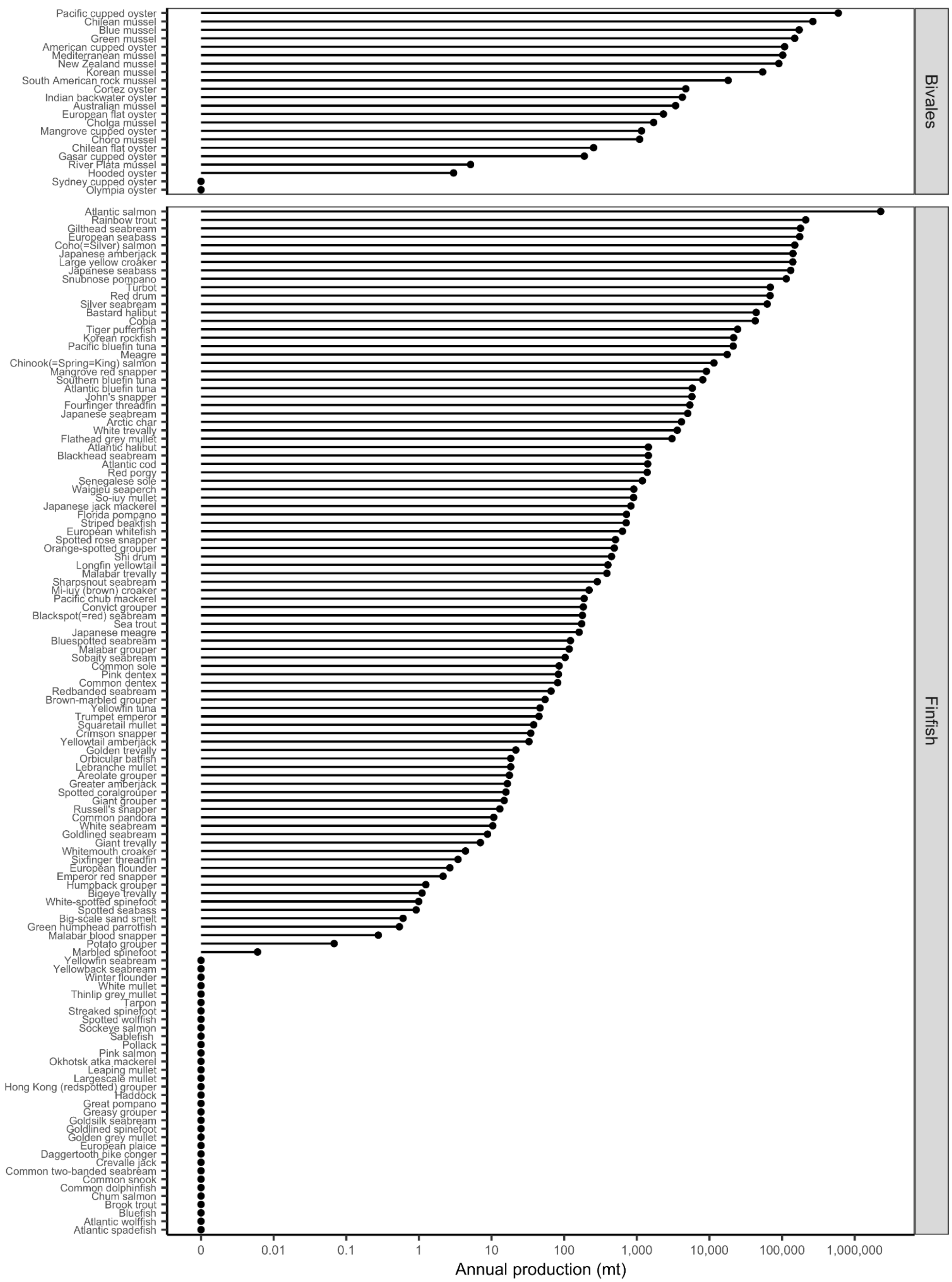
Supplementary Table 18. Pathways to expanding the ecological limits of capture fisheries on fed mariculture and how these pathways are represented in the business-as-usual and progressive reform scenarios.

Pathway	Business-as-usual scenario	Progressive reform scenario
1. Increase the amount of raw material available for reduction		
a. Reform capture fisheries	BAU fisheries management	Climate-adaptive fisheries management
b. Process more fisheries for reduction	*Not evaluated*	*Not evaluated*
b. Process more by-products for reduction	*Not evaluated*	*Not evaluated*
2. Increase the proportion of fish ingredients used by mariculture *(present day values used in both scenarios)*		
a. Reduce use in non-carnivorous terrestrial agriculture	74.5% of forage fish goes to terrestrial agriculture today	
b. Reduce use in non-carnivorous fish aquaculture	53.3% of forage fish goes to freshwater aquaculture today	
Percent of forage fish destined for reduction to mariculture:	21.2% of forage fish goes to mariculture today	
3. Reduce the amount of fish ingredients in feed	2030 FM/FO compositions	2050 FM/FO compositions
4. Reduce the feed conversion rate (i.e., increase feed efficiency)	2030 feed conversion rates	2050 feed conversion rates

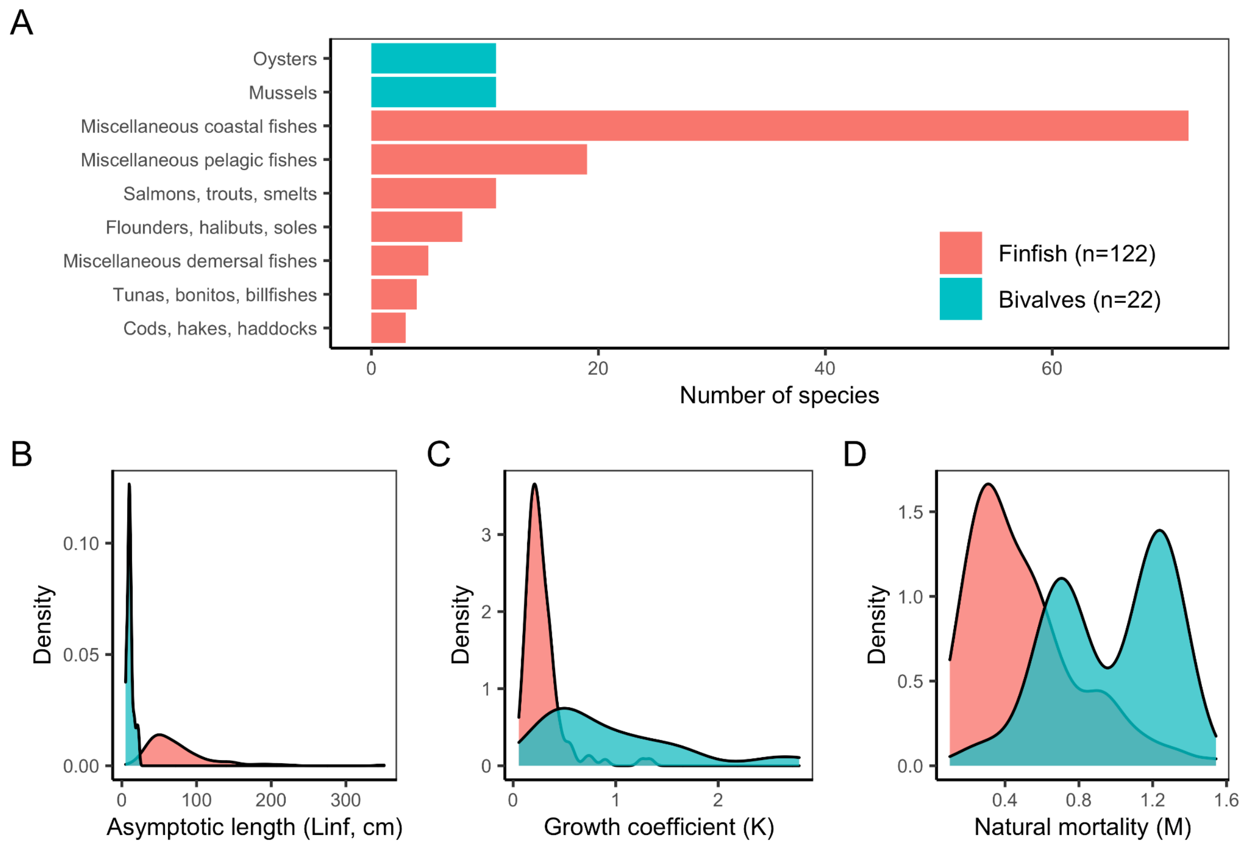
Supplementary Figures



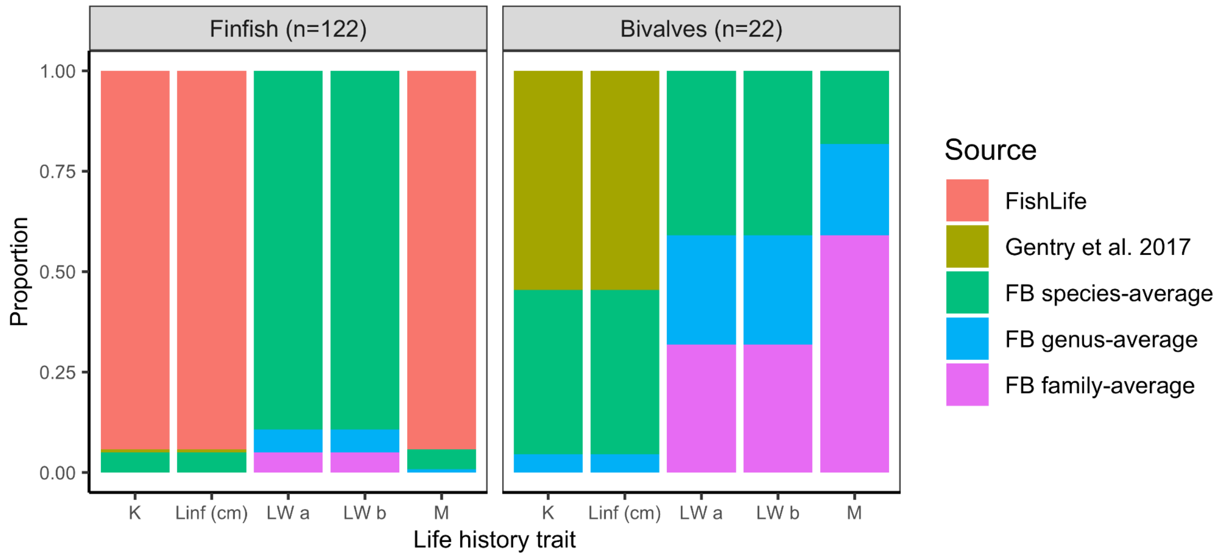
Supplementary Fig. 1. Human population size over time. Historical population growth is from the World Bank[48] and projected population growth is from the United Nations[1]. Red shading indicates the 20th and 80th percentile of the UN population projections.



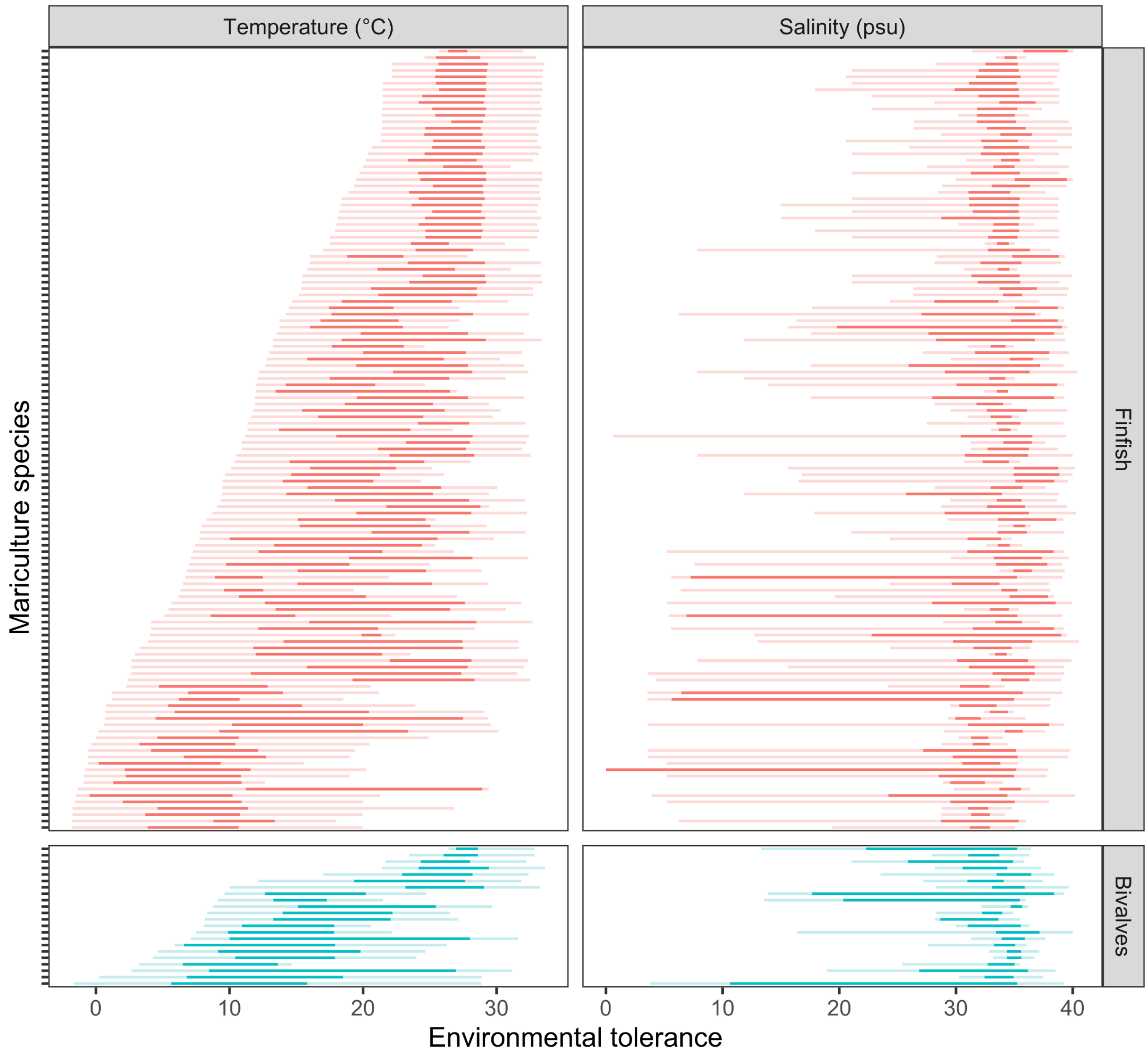
Supplementary Fig. 2. Mean annual production from 2013-2017 for the 144 species considered in the analysis. Species with zero production are currently in development.



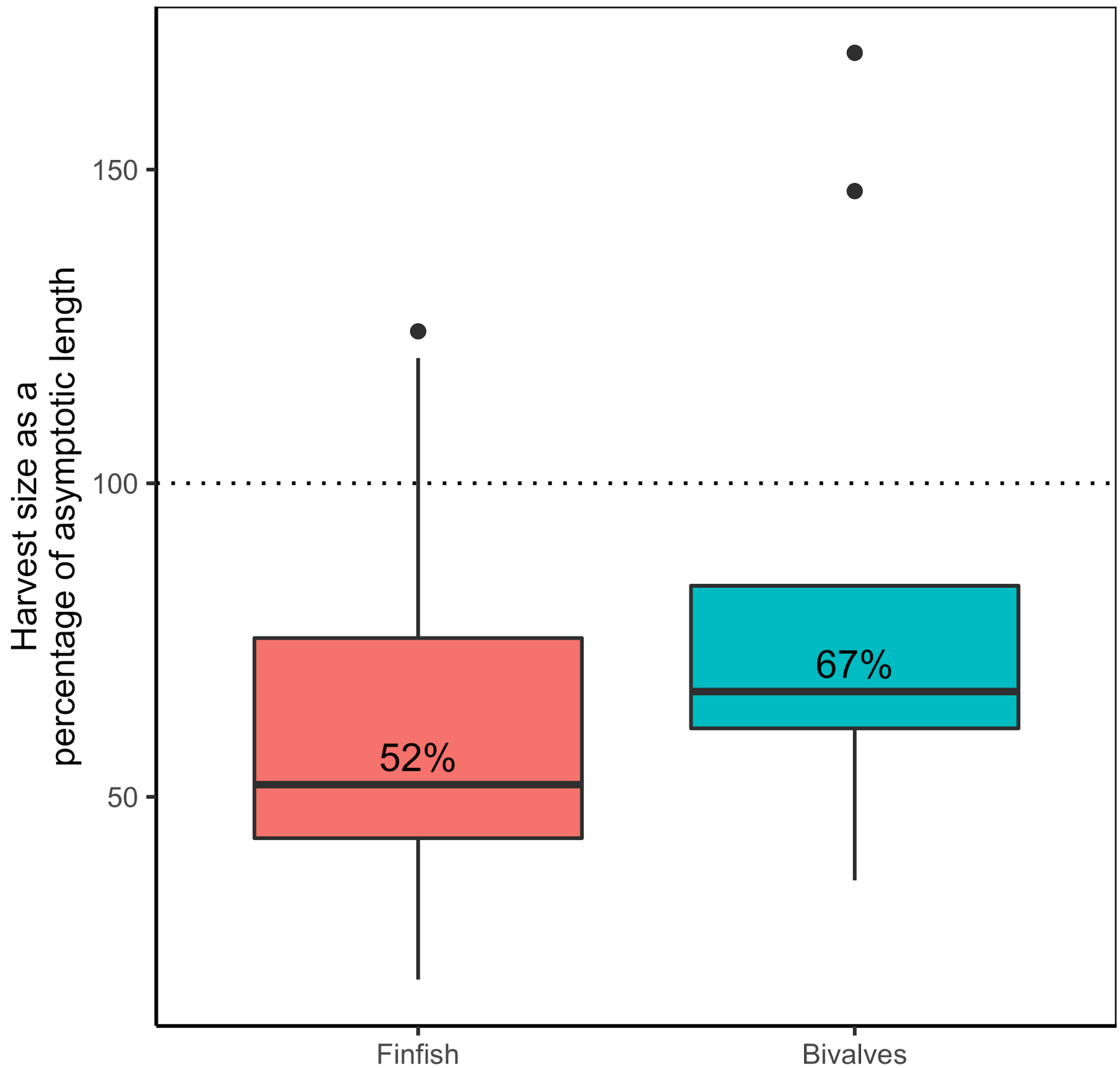
Supplementary Fig. 3. The **(A)** ISSCAAP group and von Bertalanffy **(B)** asymptotic length (L_{inf}, cm), **(C)** growth coefficient (K), and **(D)** natural mortality (M) parameters for mariculture species included in the analysis. Note: ISSCAAP is the International Standard Statistical Classification of Aquatic Animals and Plants.



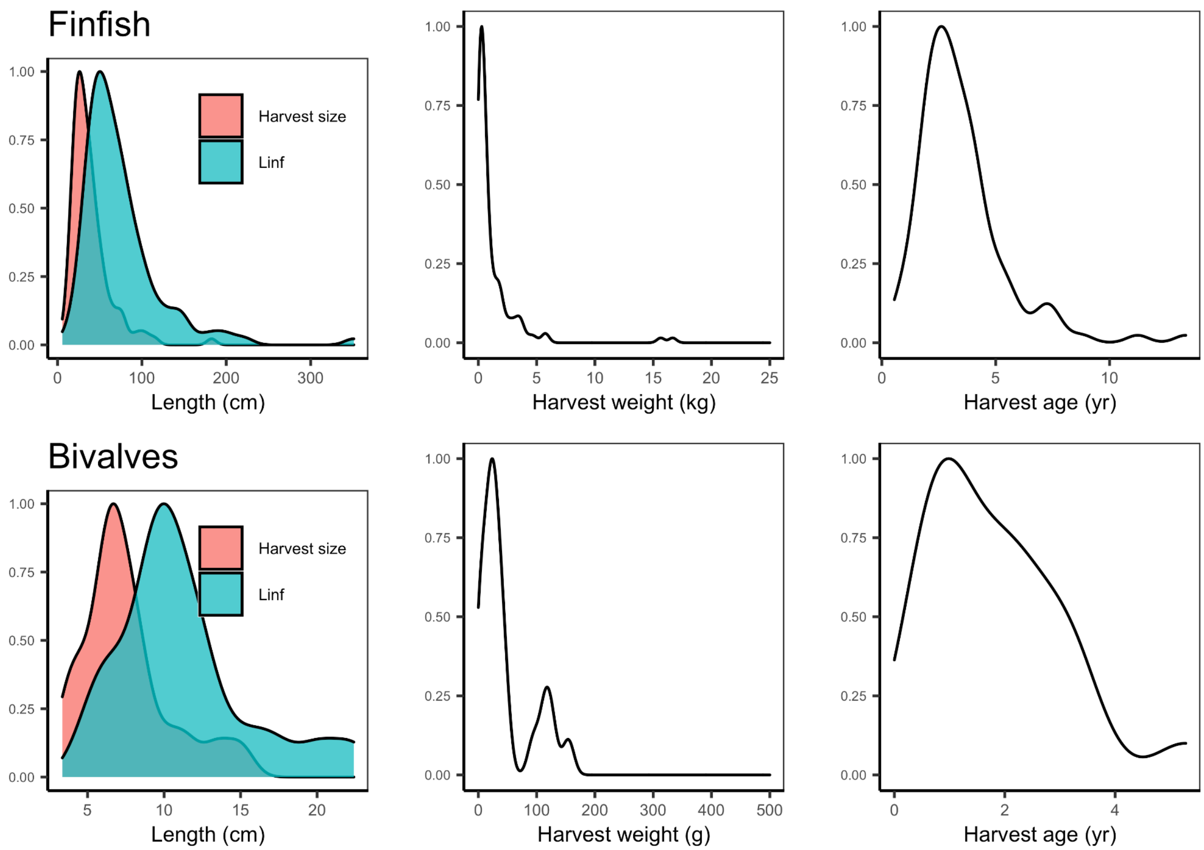
Supplementary Fig. 4. Sources for the growth (L_{inf} and K), length-weight (LW a and b), and mortality (M), parameters for species included in the analysis. FB indicates FishBase for finfish and SeaLifeBase for bivalves.



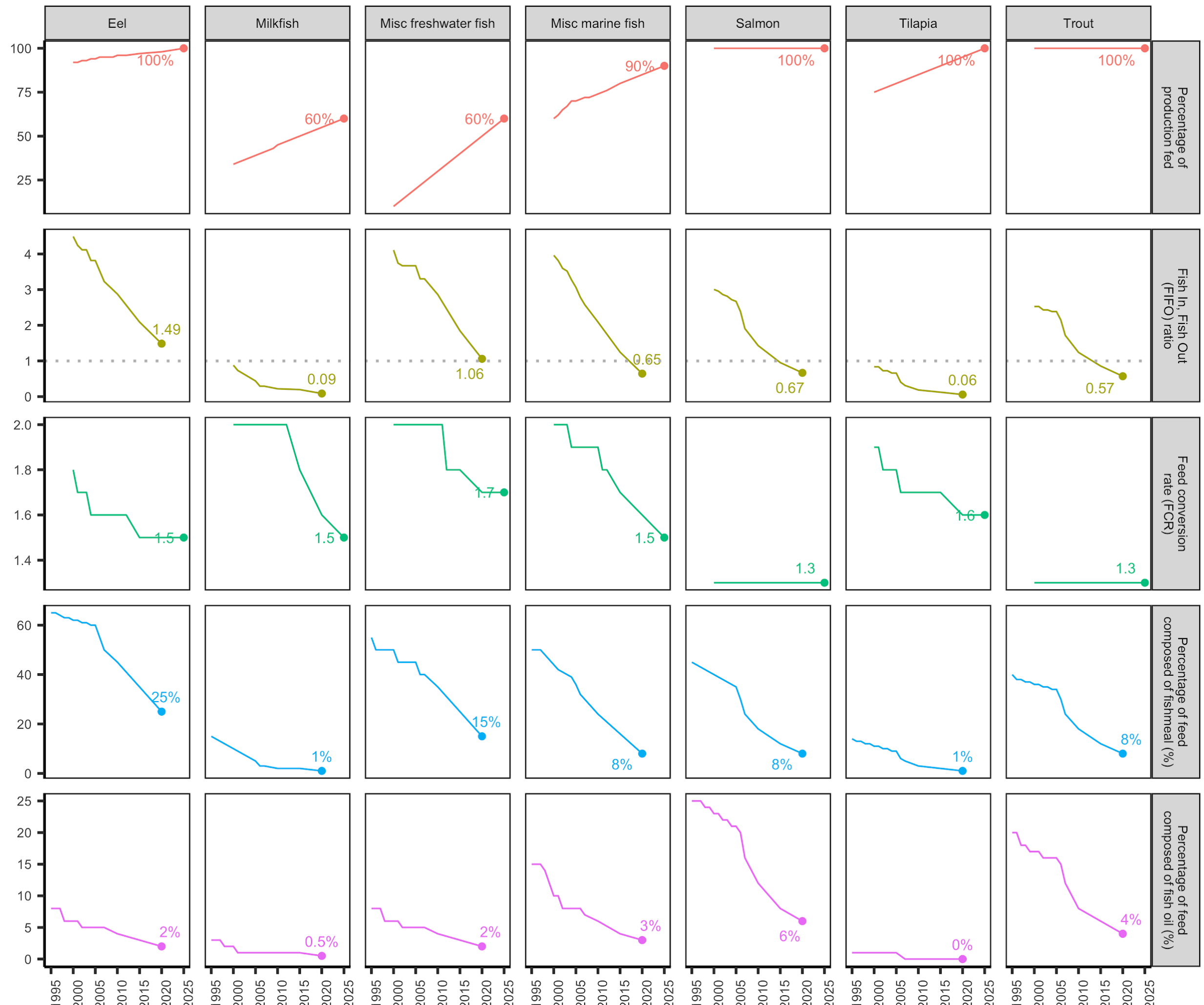
Supplementary Fig. 5. Environmental tolerances of species included in the analysis. Light shading indicates full tolerance and dark shading indicates the inner 80th percentile (i.e., 10th to 90th percentiles).



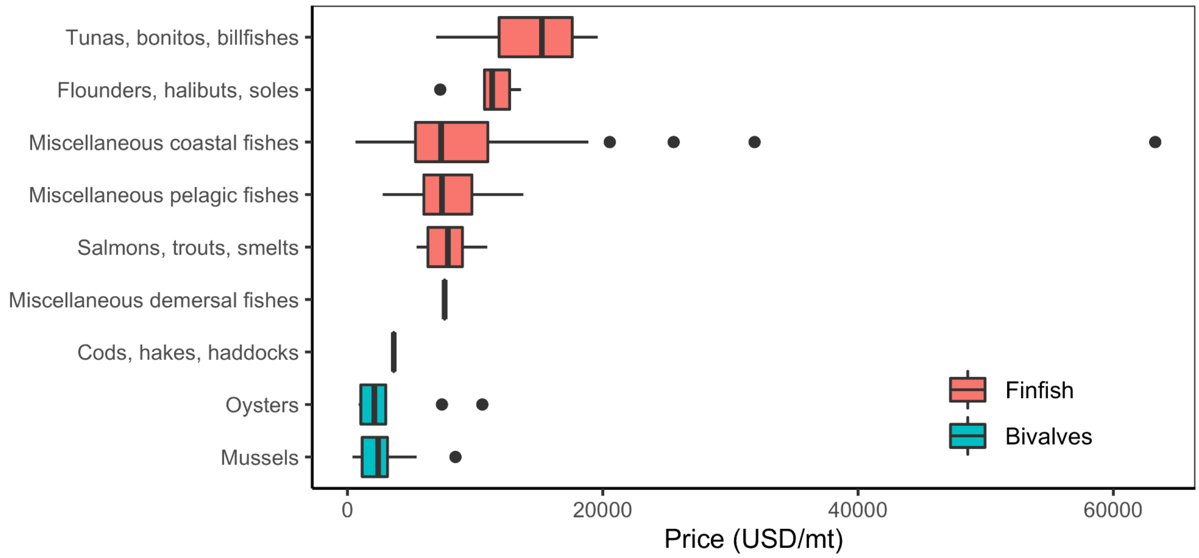
Supplementary Fig. 6. Harvest size as a percentage of asymptotic length for cultured finfish (n=38) and bivalve (n=9) species. Median harvest sizes were collected from the FAO Cultured Species Fact Sheets[22]. Harvest sizes reported in grams (the majority of finfish) were converted to lengths using length-weight parameters from FishBase and SeaLifeBase. Asymptotic lengths were sourced from FishLife for finfish and SeaLifeBase for bivalves. Values larger than one indicate species attaining larger sizes in captivity than in the wild. In the boxplots, the solid line indicates the median, the box indicates the interquartile range (IQR; 25th and 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers.



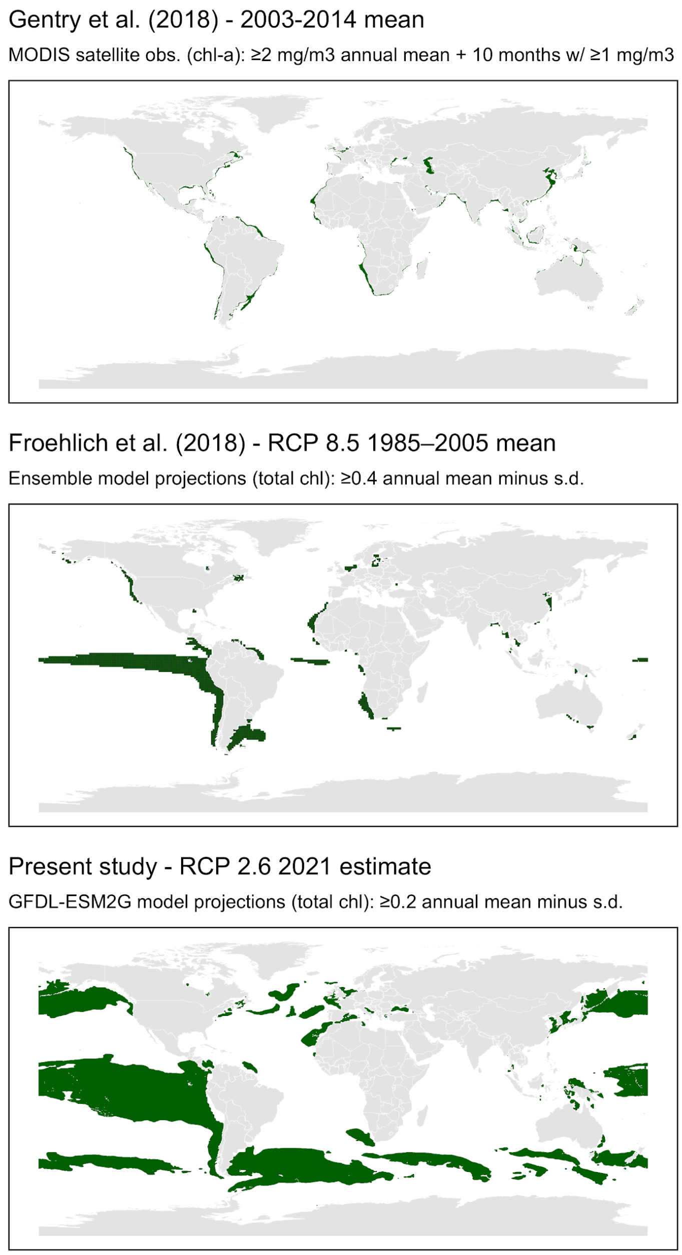
Supplementary Fig. 7. Harvest size in length and grams and time to reach it for finfish and bivalves.



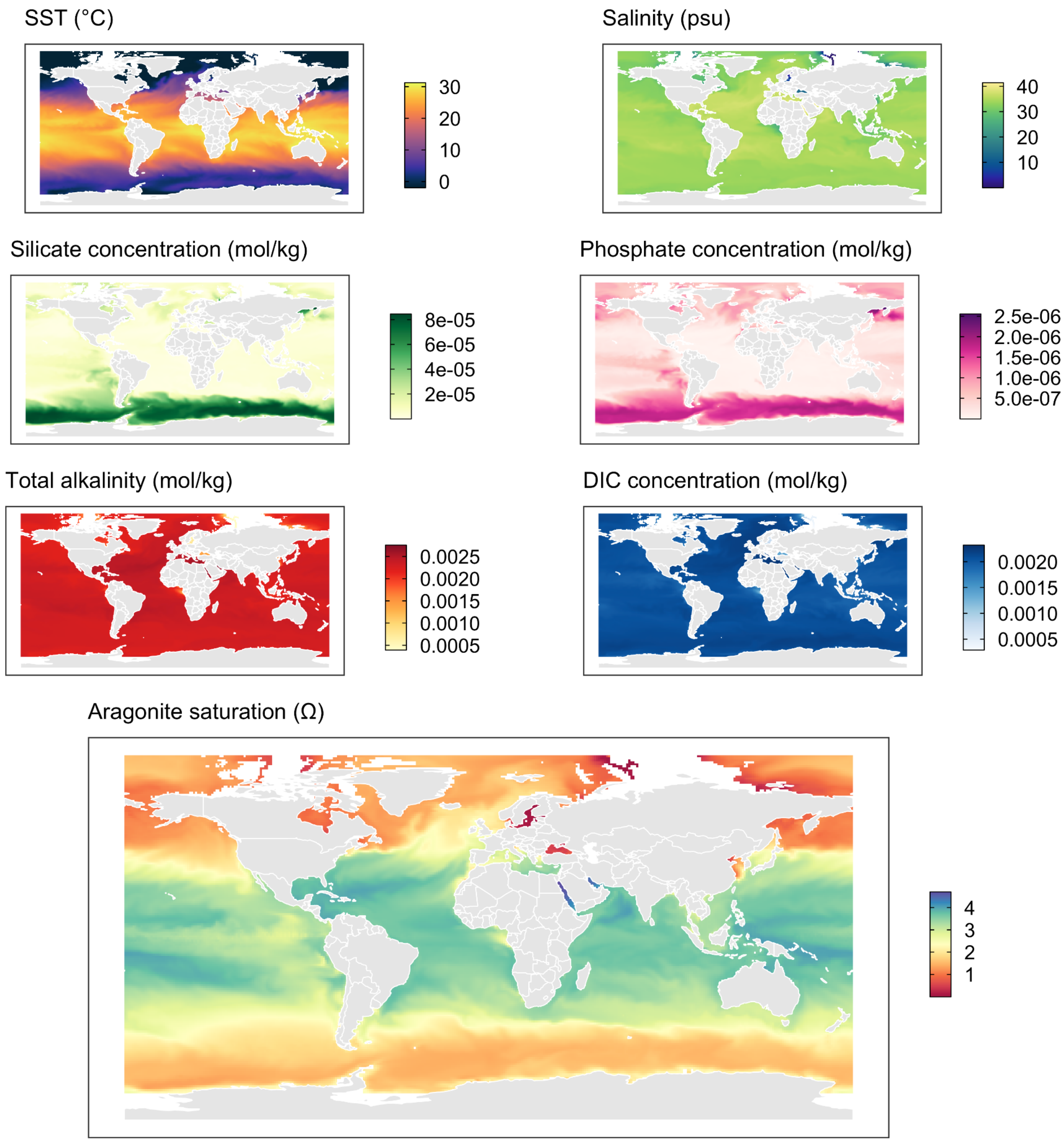
Supplementary Fig. 8. Trends in feed practices in global finfish mariculture. The percentage of finfish mariculture that is fed is increasing (top row[23]) and we assume that 100% of finfish mariculture will be fed in our projections. “Fish In, Fish Out” (FIFO) ratios are decreasing (second row) and are already below 1.0 (dotted line) for some finfish groups (derived using Equation 5). FIFO ratios are decreasing because feed conversion rates (FCR; third row[23]) and the contribution of fish ingredients to feed (fourth and fifth rows[24]) are decreasing. For tunas (not shown here), we used an FCR of 6.0 (4.6-7.4 range)[49] and the feed composition trends of salmon.



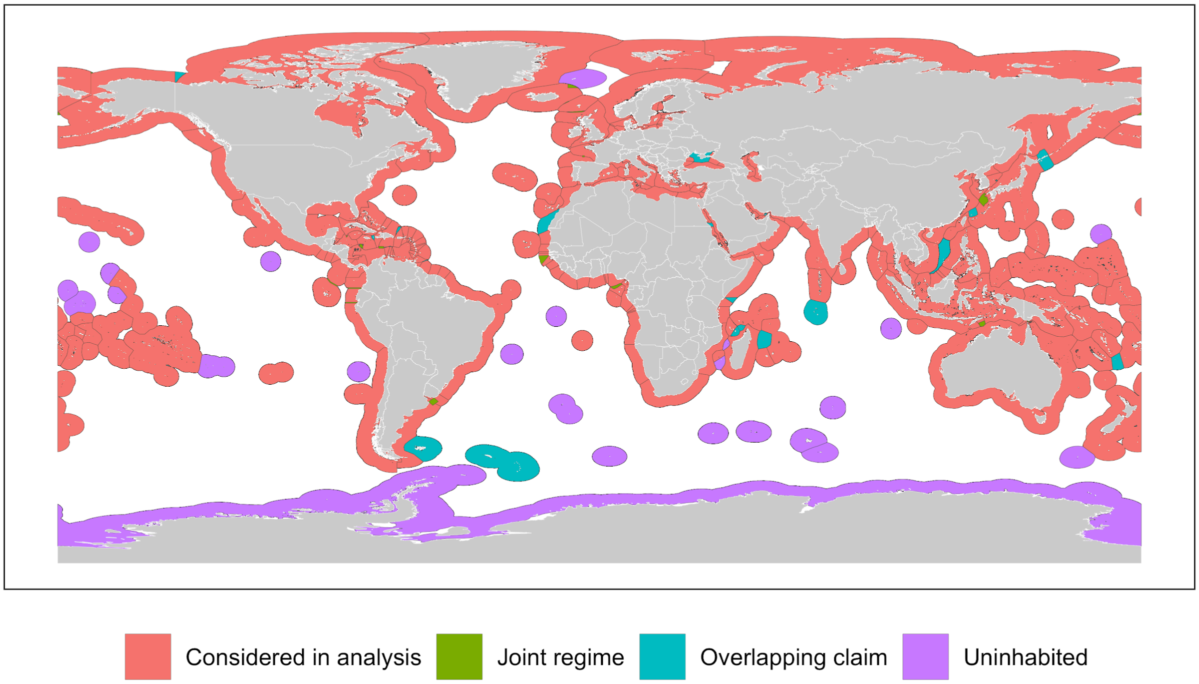
Supplementary Fig. 9. Distribution of prices for mariculture species included in the analysis by ISSCAAP group (n=144 species). We used the median ISSCAAP group price for all species within a group. In the boxplots, the solid line indicates the median, the box indicates the interquartile range (IQR; 25th and 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers.



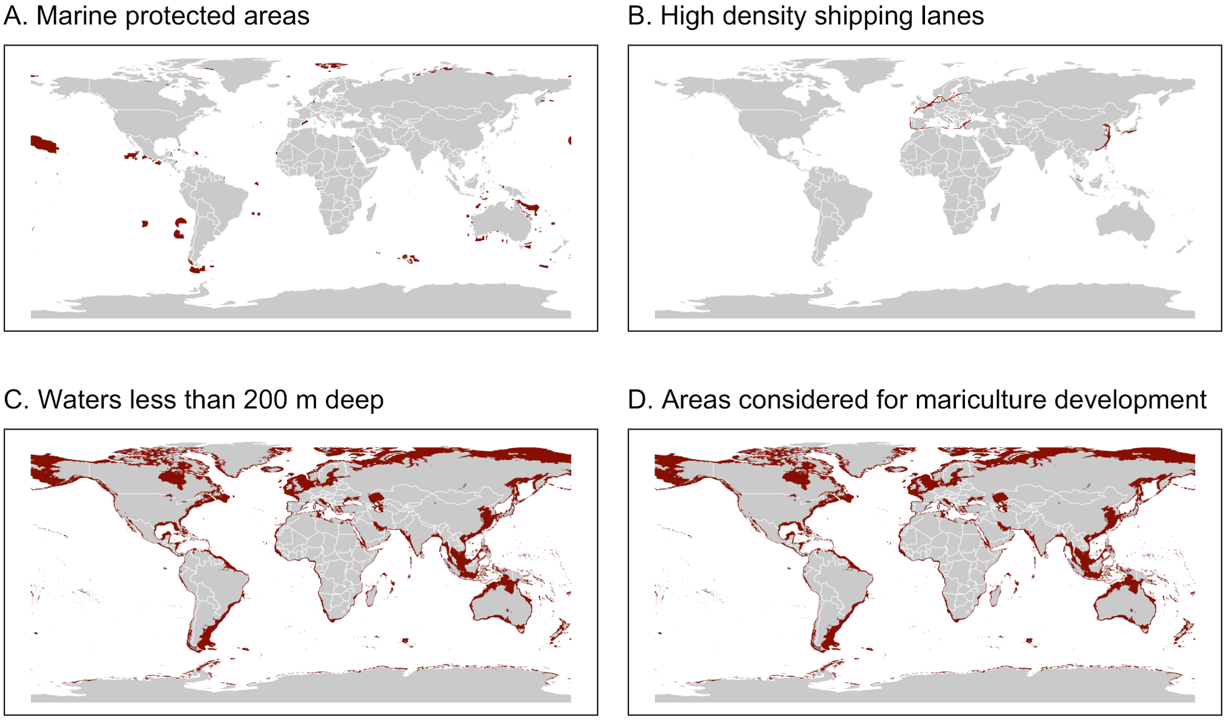
Supplementary Fig. 10. Areas with sufficiently high and stable primary production to support bivalve mariculture as determined by three global studies. Gentry et al.[16] used observations of historical chlorophyll-*a* from MODIS satellite imagery to suitable areas for bivalve mariculture, which they defined as having both mean annual chlorophyll-*a* concentrations ≥2 mg/m^3 and at least ten months with concentrations ≥1 mg/m^3. Froehlich et al.[17] (2018) used projections of total chlorophyll (not just chlorophyll-*a*) from an ensemble of earth system models to map suitable areas for bivalve mariculture and found the following threshold to best match Gentry et al.'s[16] maps in coastal areas: annual mean minus annual standard deviation ≥0.4 mg/m^3. We used projections of total chlorophyll from the GFDL-ESM2G model to map suitable areas and found the following threshold to best match Gentry et al.'s[16] maps in coastal areas for this model: annual mean minus annual standard deviation ≥0.2 mg/m^3.



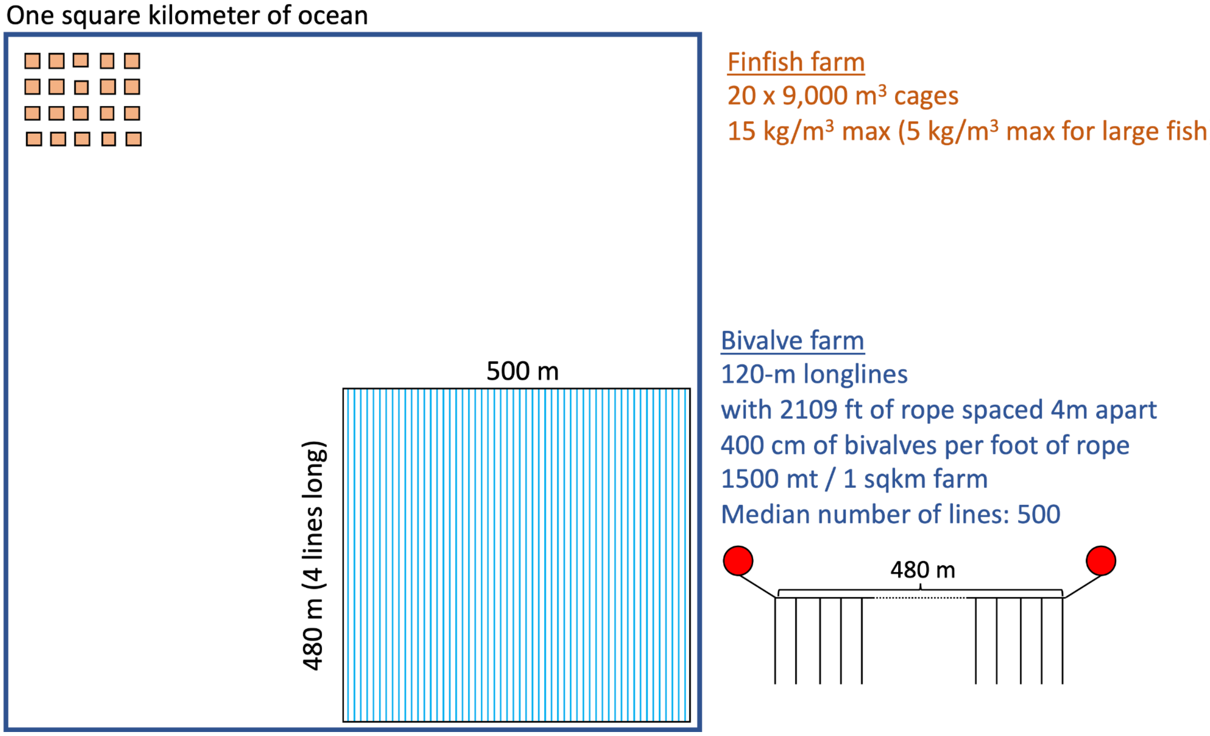
Supplementary Fig. 11. The six ocean variables used to derive aragonite saturation (Ω) using the *seacarb* R package[27]. All six variables come from the GFDL-ESM2G model.



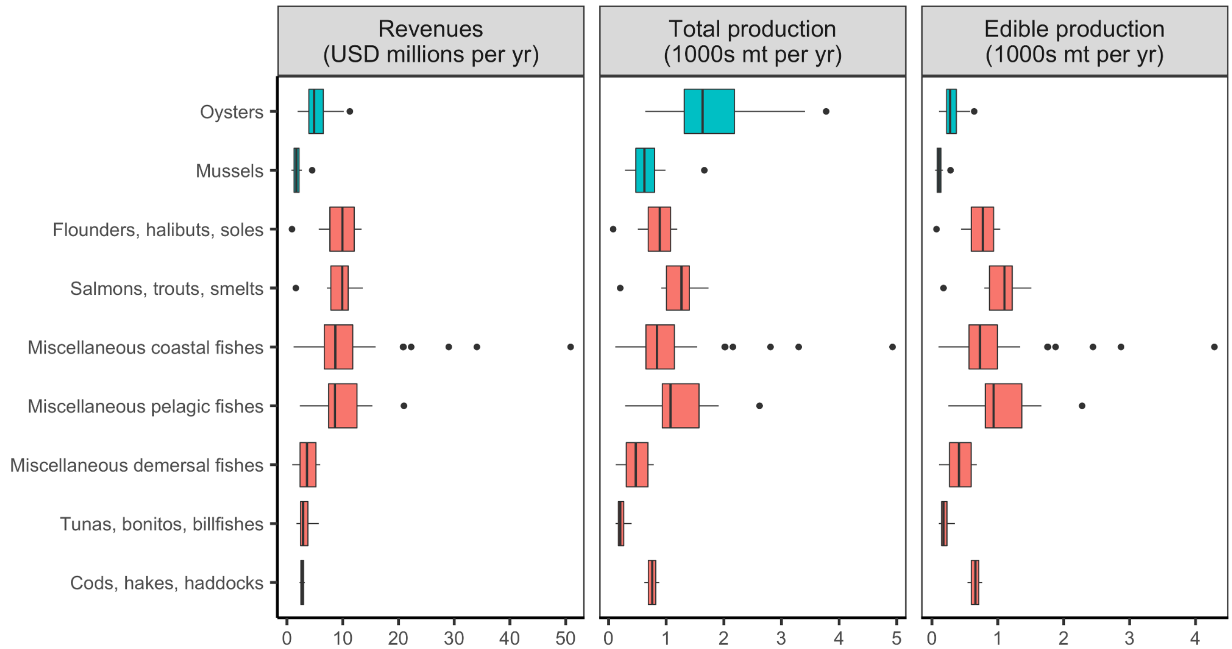
Supplementary Fig. 12. Exclusive economic zones evaluated for mariculture potential (“considered in analysis” or excluded because they either (1) surround uninhabited or sparsely inhabited islands (“uninhabited”) or (2) are disputed (“overlapping claim”) or jointly governed (“joint regime”).



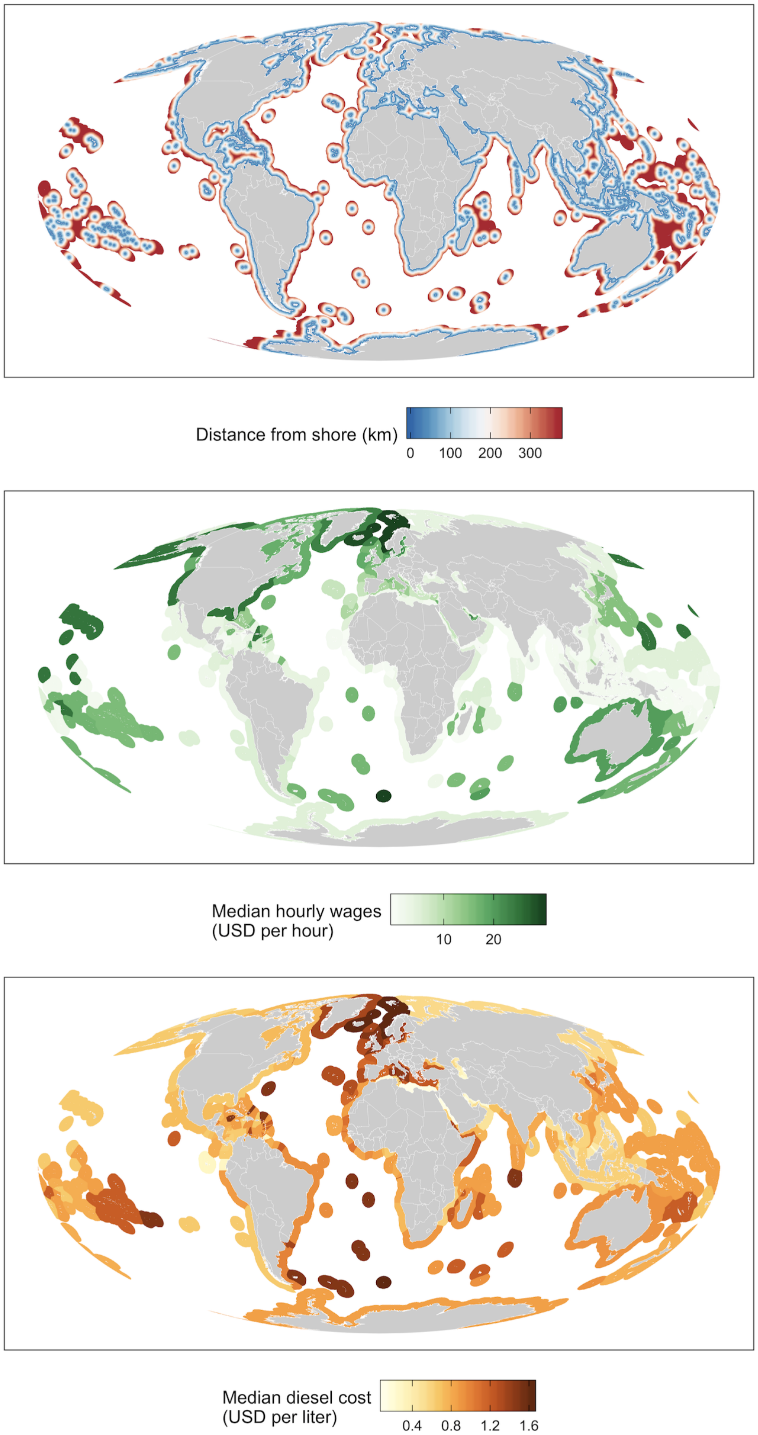
Supplementary Fig. 13. Existing ocean use and depth constraints. We excluded areas used for **(a)** marine protected areas, **(b)** high density shipping lanes, and **(c)** in waters deeper than 200 m from consideration for mariculture development. We excluded marine protected areas (“designated”, “established”, “inscribed”) in IUCN categories Ia, Ib, II, and III using the September 2019 download of the World Database of Protected Areas (WDPA). We excluded high density shipping lanes using data from Halpern et al. We identified waters shallowed than 200 m using the SRTM 30 global bathymetry dataset. Panel **(d)** shows the areas considered for mariculture development after excluding these factors and the EEZs shown in **Supplementary Fig. 12**.



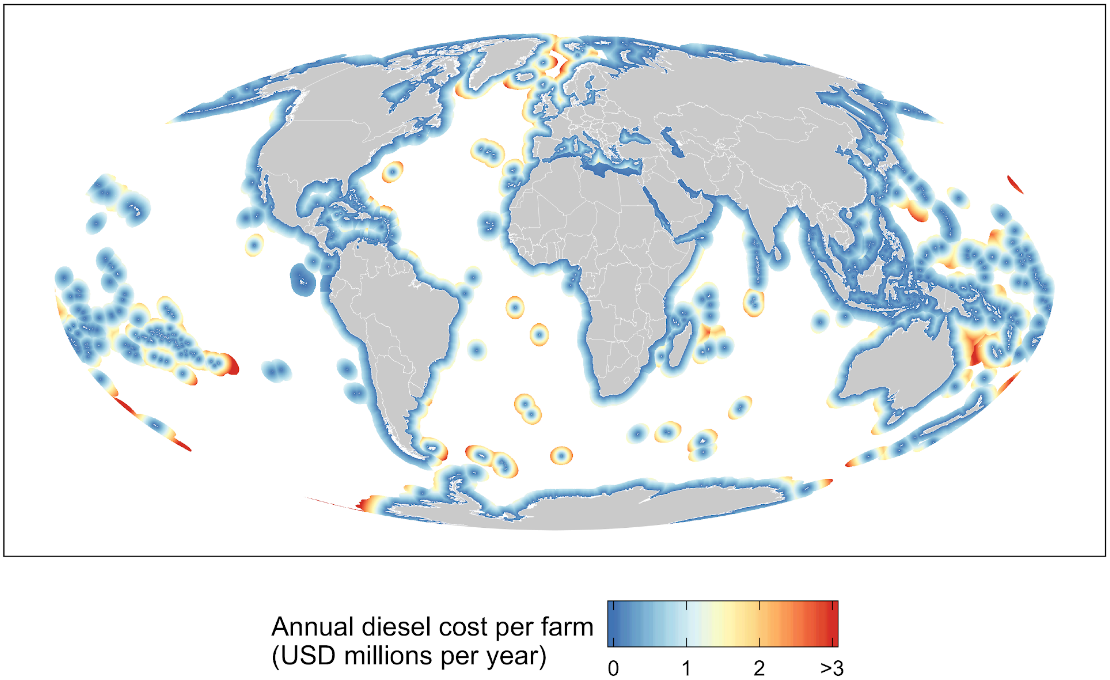
Supplementary Fig. 14. Schematic of sustainable finfish and bivalve mariculture farm designs. These farm designs are based on Gentry et al.[16] though the bivalve farm design has been modified to be more conservative. The 15 kg/m^3 harvest density for fish is consistent with the European organic standard[32] and the 1500 mt/km^2. harvest density for bivalves is equivalent to half of California's guidelines[33,50].

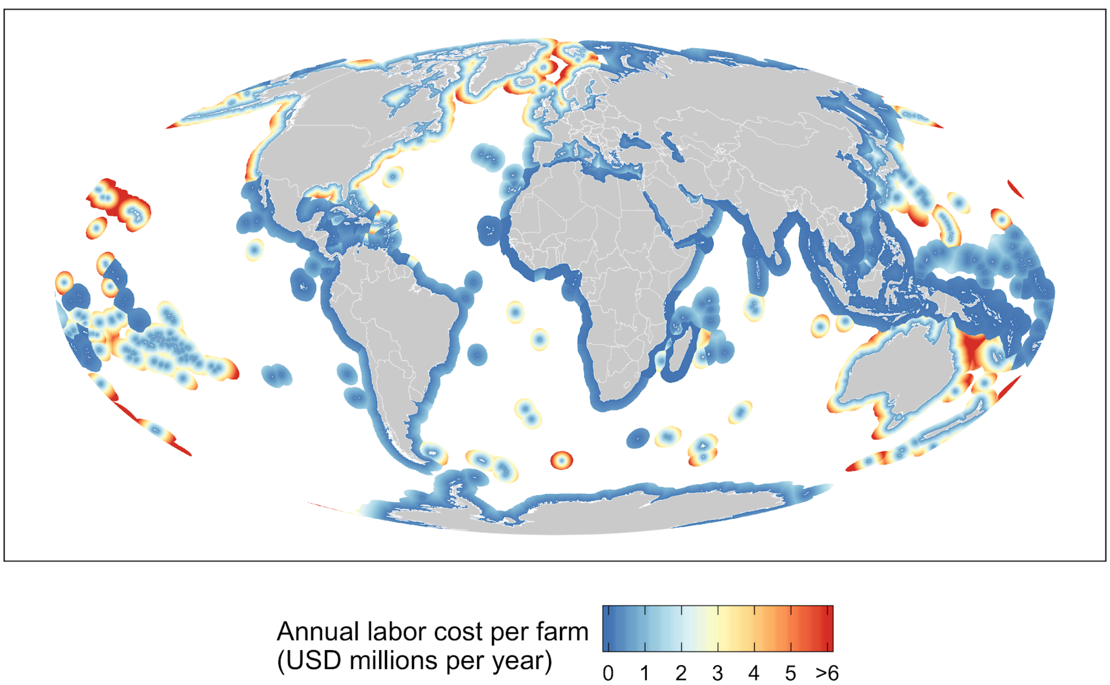


Supplementary Fig. 15. Annual revenue generation, total production, and edible production of a 1-sqkm finfish and bivalve farms by ISSCAAP group (n=144 species). Values are derived from species-specific growth rates, harvest sizes, harvest cycles (yrs), and stocking densities and group-specific prices. In the boxplots, the solid line indicates the median, the box indicates the interquartile range (IQR; 25th and 75th percentiles), the whiskers indicate 1.5 times the IQR, and the points beyond the whiskers indicate outliers.

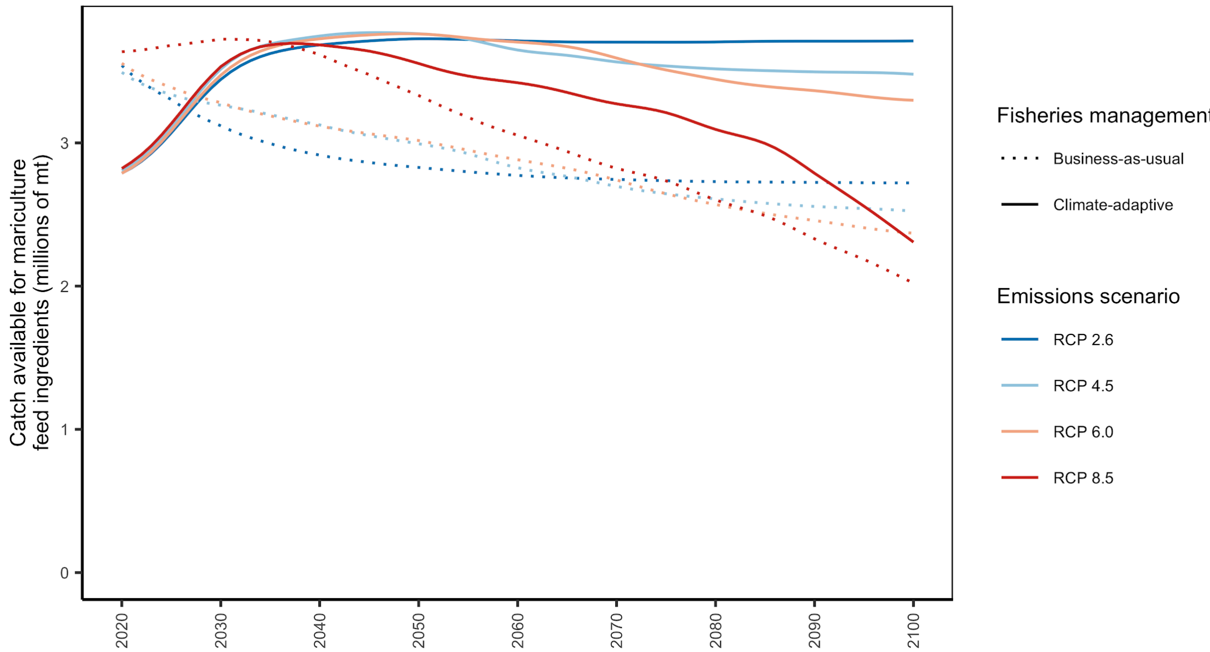


Supplementary Fig. 16. Data used to calculate annual labor and fuel costs for mariculture farms: **(a)** distance from shore (km) and country-level median **(b)** hourly wage and **(c)** diesel cost. Distance from shore was calculated using land areas in the *rnaturalearth* package[51] and hourly wage and diesel cost data are from the World Bank[34,35].

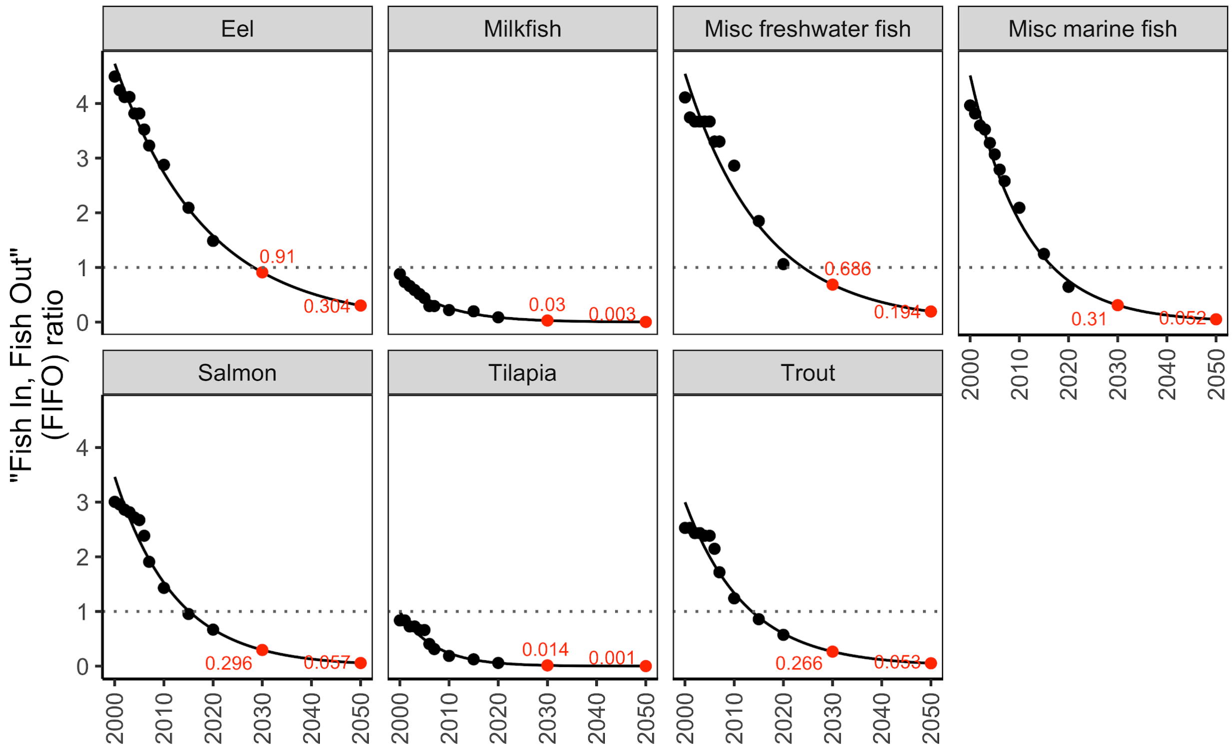




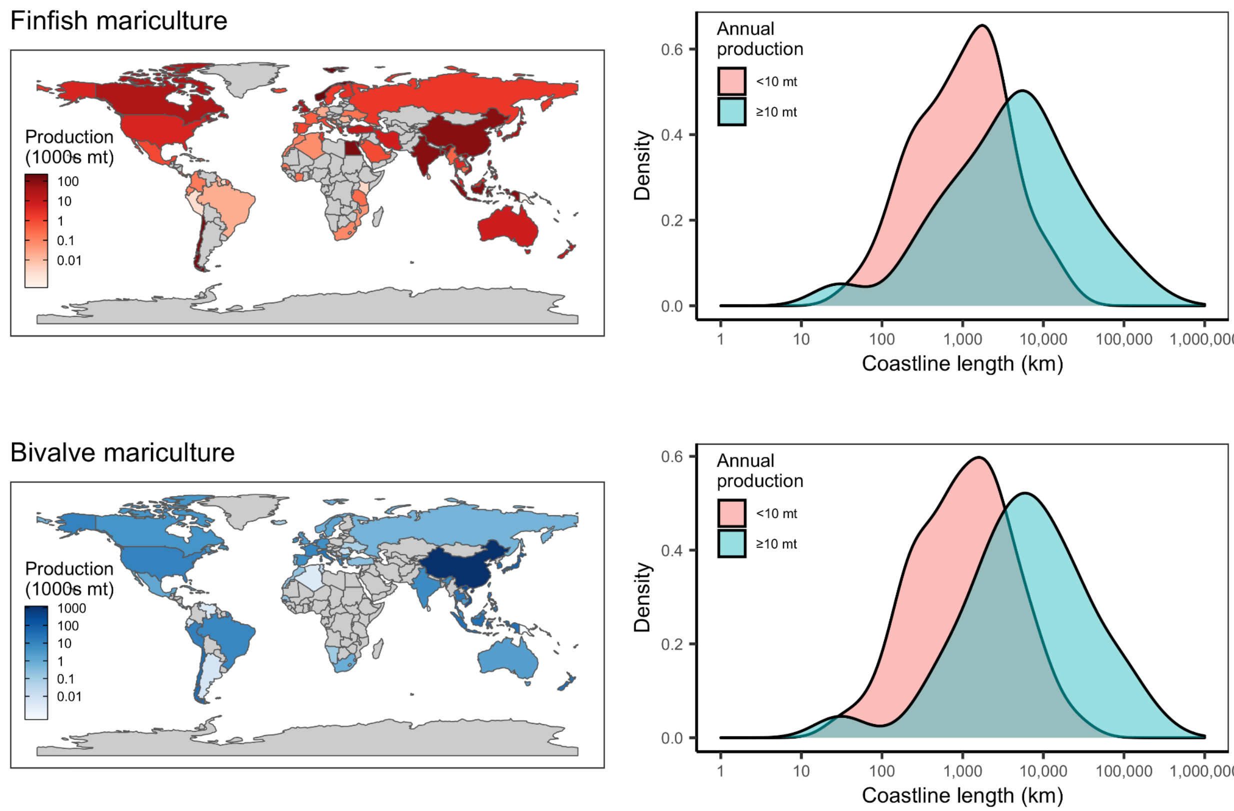
Supplementary Fig. 17. Annual fuel and labor costs per farm. Fuel cost is derived from distance from shore, vessel speed, vessel fuel efficiency, and median country-specific diesel prices. Labor cost is derived using median country-specific annual incomes and an assumption that each farm is operated by 8 workers being compensated for 40 hour weeks plus vessel transit time.



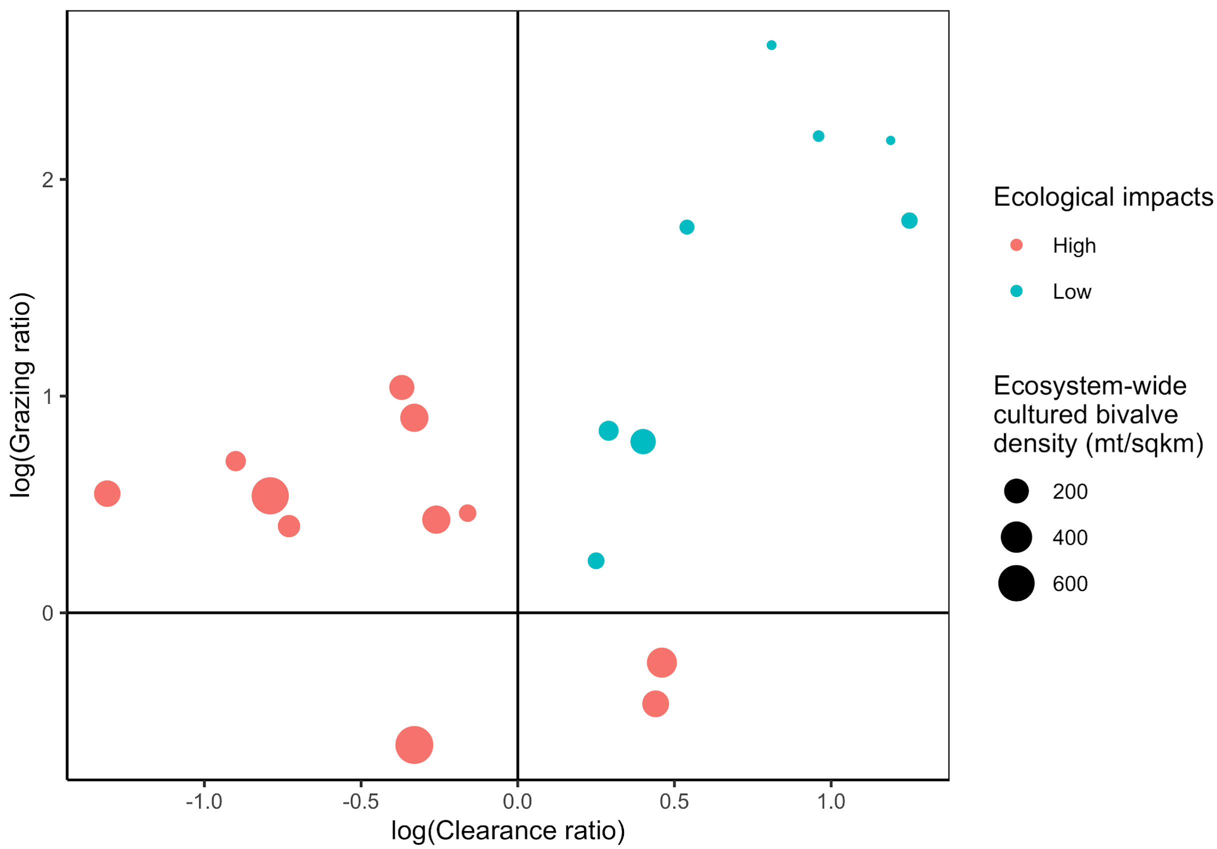
Supplementary Fig. 18. Availability of forage fish for mariculture feed under each fisheries management and climate change scenarios. In all scenarios, 18% of global fisheries landings are directed to reduction[13] and 21% of these landings are directed to mariculture feed[38].



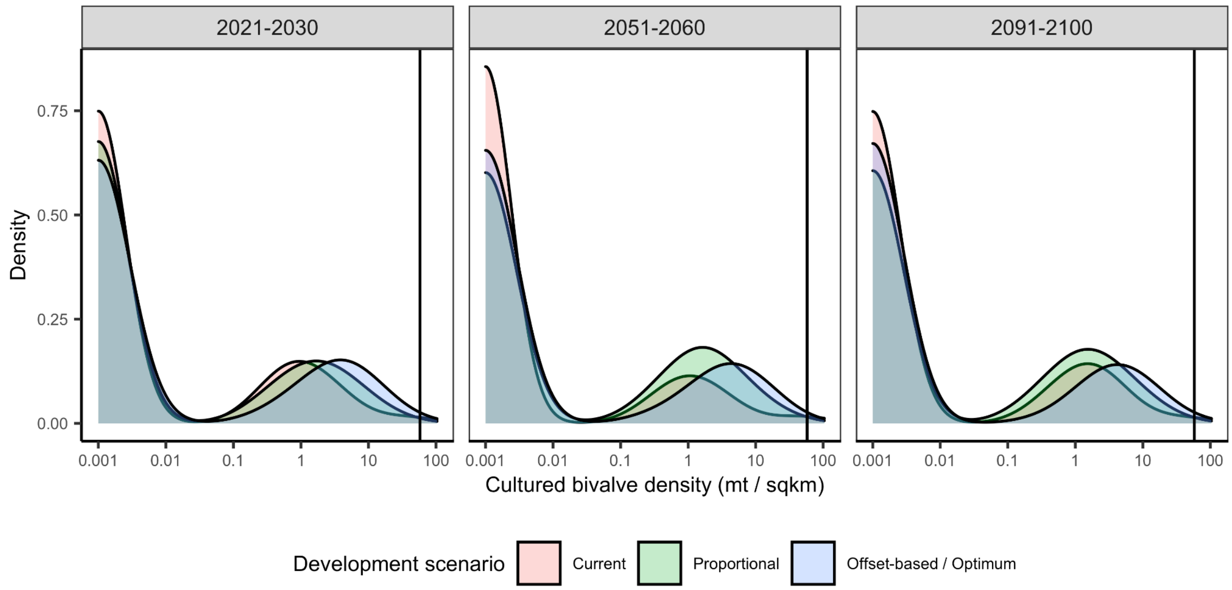
Supplementary Fig. 19. "Fish In, Fish Out" (FIFO) ratios projected for 2030 and 2050. We used the 2030 FIFO ratio projection for our business-as-usual scenario and the 2050 FIFO ratio projection for our progressive reforms scenario.



Supplementary Fig. 20. Average mariculture from 2013-2017 by country (derived from FAO[12] data) and the length of coastlines in countries with limited to no mariculture production (<10 mt/yr) and more mariculture production (>10 mt/yr).



Supplementary Fig. 21. The impact of cultured bivalve density on 19 marine ecosystems using the carrying capacity indices of Smaal and van Duren[43]. The clearance ratio is the ratio of the clearance time (time required to filter a water body) to the residence time (time required for a water body to renew itself) and describes the impact of bivalves on the system. A clearance ratio less than one (log clearance ratio less than zero) indicates a system in which bivalves exert heavy impacts on the system. The grazing ratio is the ratio of clearance time (time required to filter a water body) and the primary production time (time required to renew phytoplankton stock). A grazing ratio greater than one (or log grazing ration greater than zero) primary production exceeds bivalve filtration capacity and bivalves can be supported. We used the mean density of cultured bivalves in the upper-right quadrant as our threshold for the ecological carrying capacity of bivalve mariculture. These densities describe systems where there is ample phytoplankton to support bivalves (grazing ratio above 1) and where bivalves do not exert a negative effect on the ecosystem (clearance ratio above 1). The mean density of cultured bivalves in these large ecosystems was 57.9 mt/km^2.



Supplementary Fig. 22. Distribution of cultured bivalve density in Marine Ecoregions of the World (MEOWs)[42] in each period under each development scenario. The vertical line marks the 59.7 mt/km^2 ecosystem-wide carrying capacity for cultured bivalves that we derived based on the review and carrying capacity indices of Smaal and van Duren[43]. Note: the x-axis is in log-scale (zero density recoded as 0.001 mt/km^2 for visualization) and the distributions of mariculture development in the offset-based and optimum development scenarios are identical.