**Table S1**. Representative Concentration Pathways (RCPs) evaluated in the analysis.

|  |  |  |
| --- | --- | --- |
| **Scenario** | **Projected**  **warming (°C)** | **Description** |
| RCP 2.6 | 1.0 (0.3-1.7) | Peak in radiative forcing at ~3.0 W/m2 (~490 ppm CO2 eq) before 2100 and then decline to 2.6 W/m2 by 2100 |
| RCP 4.5 | 1.8 (1.1-2.6) | Stabilization without overshoot pathway to 4.5 W/m2 (~650 ppm CO2 eq) at stabilization after 2100 |
| RCP 6.0 | 2.2 (1.4-3.1) | Stabilization without overshoot pathway to 6.0 W/m2 (~850 ppm CO2 eq) at stabilization after 2100 |
| RCP 8.5 | 3.7 (2.6-4.8) | Rising radiative forcing pathway leading to 8.5 W/m2 (~1370 ppm CO2 eq) by 2100 |

**Table S2.** 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 |

**Table S3.** Harvest control rules used in the management scenarios.\*

|  |
| --- |
| **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 BMSY), 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. |

\* See the Gaines et al. [19] supplementary information for more details on the management scenarios and harvest control rules.

**Table S4.** Differences in the modelling approaches of four studies of mariculture production potential1.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  | **Gentry et al. (2017)** | **Froehlich et al. (2018)** | **Costello et al. (2019)** | **Present study** |
| **Parameter** | **Biological potential today** | **Biological potential under CC** | **Economic potential today** | **Economic potential under CC** |
| *Model specifications* |  |  |  |  |
| Number of species | 180 (120 finfish, 60 bivalves) | 180 (120 finfish, 60 bivalves) | 180 (120 finfish, 60 bivalves) | 189 (136 finfish, 53 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/depth | 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, SAL, CHL/acidification (bivalves) |
| 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

**Table S5.** Actions taken to explicitly account for the constraints on mariculture expansion outlined by [(Troell et al., 2017)](https://www.zotero.org/google-docs/?G3fNCW) in their response to [(Gentry et al., 2017)](https://www.zotero.org/google-docs/?HeZ2c8).

|  |  |  |
| --- | --- | --- |
|  | **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. |

**Table S6.** Feed parameters by feed group (FIFO = “fish in, fish out”).

|  |  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
|  | **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 |

**Table S7.** Live-weight to edible meat conversion factors.

|  |  |  |
| --- | --- | --- |
| **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 |

**Table S4.** Environmental variables and lethal limits used to map the suitability of ocean cells for finfish or bivalve mariculture.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Code (native units)1** | **Variable (converted units)2** | **Finfish limits** | **Bivalves limits** | **Limit reference** |
| tos (K) | Temperature (°C) | species-specific | species-specific | AquaMaps |
| so (psu) | Salinity (psu) | species-specific | species-specific | AquaMaps |
| o2 (mol/m3) | Dissolved oxygen concentration (mol/m3) | > 0.2757 mol/m3 (> 4.41 mg/L) | > 0.1244 mol/m3 (> 1.99 mg/L) | Gentry et al. (2017) |
| chl (kg/m3) | Total chlorophyll concentration (mg/m3) | 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) |

1 Name and units of the environmental variable output by CMIP5 earth system models including the GDFL-ESM2G used here.

2 All variables reflect values at the ocean surface.

**Table S5.** Environmental variables used to calculate aragonite saturation (Ω) using the *seacarb* R package.

|  |  |
| --- | --- |
| **Code (native units)1** | **Variable (converted units)2** |
| 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.

**Table S6.** 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 F√©lix and San Ambrosio |
| Colombia | Bajo Nuevo Bank |
| Colombia | Quitasue√±o 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 | Kergu√©len |
| 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 |

**Table S6.** Finfish and bivalve farm specifications based on Gentry et al. (2017).

|  |  |
| --- | --- |
| **Parameter** | **Value** |
| *Finfish farm (1 sq. km)* |  |
| *Specifications* |  |
| Number of cages | 24 |
| Cage volume (m3) | 9,000 |
| Harvest density (kg/m3) - Linf < 140 cm | 15 |
| Harvest density (kg/m3) - Linf ≥ 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 |
| Total number stocked | 888,283 |
| Annual production (mt) | 1,258 |
| Annual revenues (USD) @ US$7,836/mt | 9,858,049 |
|  |  |
| *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 | 78,617,588 |
| Annual production (mt) | 446.6 |
| Annual revenues (USD) @ US$2,718/mt | 1,213,788 |

**Table S7.** 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 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 S8.** Cost parameters for finfish mariculture from Rubino 2008.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Type** | **Description** | **Unit** | **Baseline value** | **High-end value** |
| *Equipment costs* | |  |  |  |
| capital | cage purchase | US$/m3 | 15 | 25 |
| capital | cage mooring and installation1 | US$/m3 | 3 | 3 |
| annual | cage operating and maintenance2 | 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$/farm | 0 | 10,000 |
| annual | feed3 | US$/kg | 2.00 |  |
|  |  |  |  |  |
| *Plans* |  |  |  |  |
| annual | insurance4 | 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$/farm | 0 | 1615.2 |
|  |  |  |  |  |
| *Other costs* |  |  |  |  |
| annual | on shore cost5 | US$/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 S9.** Cost parameters for bivalve mariculture from Rubino 2008.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
|  |  |  | **Baseline value** | **High-end value** |
| **Type** | **Description** | **Units** | **(used vessel)** | **(new vessel)** |
| *Equipment costs* | |  |  |  |
| capital | longline equipment and installation1 | US$/longline | 10,000 |  |
| annual | expendable supplies2 | US$/longline/year | 1,700 |  |
|  |  |  |  |  |
| *Vessel costs* | |  |  |  |
| capital | vessel (+cost of upgrades to used vessels3) | US$/vessel | 95,000 | 800,000 |
| annual | vessel maintenance | US$/vessel/year | 10,000 | 30,000 |
| annual | vessel equipment maintenance | US$/vessel/year | 5,000 |  |
|  |  |  |  |  |
| *Other costs* |  |  |  |  |
| annual | on shore cost4 | US$/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 S15**. Pathways to expanding the ecological limits of capture fisheries on fed mariculture and how these pathways are represented in the base case 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 |