**Table S1.** 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) | 200 (136 finfish, 64 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, 2051, and 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 |
| 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 S2.** Feed parameters by feed group.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Feed group** | **Feed conversion ratio (FCR)** | **Percentage of fishmeal in feed** | **Percentage of fish oil in feed** | **Today’s FIFO ratio1** | **Projected FIFO ratio2** |
| Eel | 1.5 | 25% | 2% | 1.49 | 0.30 |
| Milkfish | 1.5 | 1% | 0.50% | 0.09 | 0.00 |
| Misc freshwater fish | 1.7 | 15% | 2% | 1.06 | 0.19 |
| Misc marine fish | 1.5 | 8% | 3% | 0.65 | 0.05 |
| Salmon | 1.3 | 8% | 6% | 0.67 | 0.06 |
| Tilapia | 1.6 | 1% | 0% | 0.06 | 0.00 |
| Trout | 1.3 | 8% | 4% | 0.57 | 0.05 |

1 FIFO = Fish In, Fish Out ratio.

2 FIFO ratio projected for 2050 as shown in **Figure SX**.

**Table S3.** Representative Concentration Pathways (RCPs) evaluated in the analysis\*.

|  |  |  |
| --- | --- | --- |
| **Scenario** | **Description\*\*** | **Reference** |
| RCP 2.6 | 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 | van Vuuren et al. 2006, 2007 |
| RCP 4.5 | Stabilization without overshoot pathway to 4.5 W/m2 (~650 ppm CO2 eq) at stabilization after 2100 | Clarke et al. 2007; Smith & Wigley 2006; Wise et al. 2009 |
| RCP 6.0 | Stabilization without overshoot pathway to 6.0 W/m2 (~850 ppm CO2 eq) at stabilization after 2100 | Fujino et al. 2006; Hijioka et al. 2008 |
| RCP 8.5 | Rising radiative forcing pathway leading to 8.5 W/m2 (~1370 ppm CO2 eq) by 2100 | Riahi et al. 2007 |

\*\* Based on Table 2 in van Vuuren et al. 2011.

**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 | > 1.0 | Froehlich et al. (2018) |

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* |  |
| Number of longlines | 100 |
| Longline length (m) | 4,000 |
| Harvest density (cm/foot) | 400 |
|  |  |
| *Example farm: Blue mussel* |  |
| Length at harvest (cm) | 5.9 |
| Weight at harvest (g) | 19.1 |
| Time to harvest (yr) | 3.4 |
| Total number stocked | 89,165,363 |
| Annual production (mt) | 506 |
| Annual revenues (USD) @ US$2,718/mt | 1,376,857 |

**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 S11**. 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 by-products for reduction | *Not evaluated due to lack of data* | *Not evaluated due to lack of data* |
|  |  |  |
| 2. Increase the proportion of fish ingredients used by mariculture |  |  |
| a. Reduce use in non-carnivorous terrestrial agriculture | 74.5% of forage fish to aquaculture | 74.5% of forage fish to aquaculture |
| b. Reduce use in non-carnivorous fish aquaculture | 28.5% of this supply to mariculture | 100% of this supply to mariculture |
| Percent of forage fish destined for reduction to mariculture: | 21.2% of forage fish to mariculture | 74.5% of forage fish to mariculture |
|  |  |  |
| 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 |

**Table A11.** 2100 production potential for finfish mariculture under climate change in each feed scenario and development pattern.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Scenario** | **RCP** | **Area developed (thsds. of sqkm)** | **Production potential (millions of mt)** | **Profit potential (billions of USD)** |
| ***Business-as-usual*** |  |  |  |  |
| Current development | RCP 2.6 | 4.2 | 7.0 | 36.3 |
| Current development | RCP 4.5 | 4.0 | 6.8 | 34.7 |
| Current development | RCP 6.0 | 3.9 | 6.3 | 29.1 |
| Current development | RCP 8.5 | 3.2 | 5.5 | 25.3 |
| Equal development | RCP 2.6 | 5.5 | 8.9 | 51.2 |
| Equal development | RCP 4.5 | 5.3 | 8.6 | 49.3 |
| Equal development | RCP 6.0 | 5.0 | 8.1 | 46.3 |
| Equal development | RCP 8.5 | 4.5 | 7.3 | 40.9 |
| Need-based development | RCP 2.6 | 3.1 | 5.1 | 28.3 |
| Need-based development | RCP 4.5 | 2.8 | 4.6 | 25.5 |
| Need-based development | RCP 6.0 | 2.6 | 4.1 | 20.2 |
| Need-based development | RCP 8.5 | 2.1 | 3.6 | 16.8 |
| Rational development | RCP 2.6 | 5.5 | 8.9 | 51.3 |
| Rational development | RCP 4.5 | 5.3 | 8.6 | 49.5 |
| Rational development | RCP 6.0 | 5.0 | 8.1 | 46.7 |
| Rational development | RCP 8.5 | 4.5 | 7.3 | 41.9 |
| ***Progressive reform*** |  |  |  |  |
| Current development | RCP 2.6 | 134.7 | 223.7 | 1160.9 |
| Current development | RCP 4.5 | 129.6 | 217.6 | 1118.5 |
| Current development | RCP 6.0 | 129.8 | 208.7 | 957.1 |
| Current development | RCP 8.5 | 92.3 | 159.7 | 679.7 |
| Equal development | RCP 2.6 | 150.8 | 243.5 | 1300.6 |
| Equal development | RCP 4.5 | 149.0 | 238.5 | 1244.1 |
| Equal development | RCP 6.0 | 145.9 | 228.2 | 1112.9 |
| Equal development | RCP 8.5 | 106.2 | 176.1 | 786.3 |
| Need-based development | RCP 2.6 | 140.2 | 230.5 | 1260.9 |
| Need-based development | RCP 4.5 | 138.1 | 224.5 | 1205.5 |
| Need-based development | RCP 6.0 | 135.5 | 214.0 | 1003.3 |
| Need-based development | RCP 8.5 | 95.4 | 162.2 | 704.6 |
| Rational development | RCP 2.6 | 152.6 | 247.6 | 1423.2 |
| Rational development | RCP 4.5 | 148.5 | 240.9 | 1384.7 |
| Rational development | RCP 6.0 | 141.9 | 230.2 | 1320.5 |
| Rational development | RCP 8.5 | 109.3 | 177.3 | 1013.6 |