Expanding ocean food production under climate change

https://doi.org/10.1038/s41586-022-04674-5

Received: 31 January 2020

Accepted: 22 March 2022

Christopher M. Free[1,2], Reniel B. Cabral[1,2,3], Halley E. Froehlich[4,5], Willow Battista[6], Elena Ojea[7], Erin O'Reilly[1,2,8], James E. Palardy[9], Jorge García Molinos[10,11,12], Katherine J. Siegel[13], Ragnar Arnason[14], Marie Antonette Juinio-Meñez[15], Katharina Fabricius[16], Carol Turley[17] & Steven D. Gaines[1]

As the human population and demand for food grow[1], the ocean will be called on to provide increasing amounts of seafood. Although fisheries reforms and advances in offshore aquaculture (hereafter 'mariculture') could increase production[2], the true future of seafood depends on human responses to climate change[3]. Here we investigated whether coordinated reforms in fisheries and mariculture could increase seafood production per capita under climate change. We find that climate-adaptive fisheries reforms will be necessary but insufficient to maintain global seafood production per capita, even with aggressive reductions in greenhouse-gas emissions. However, the potential for sustainable mariculture to increase seafood per capita is vast and could increase seafood production per capita under all but the most severe emissions scenario. These increases are contingent on fisheries reforms, continued advances in feed technology and the establishment of effective mariculture governance and best practices. Furthermore, dramatically curbing emissions is essential for reducing inequities, increasing reform efficacy and mitigating risks unaccounted for in our analysis. Although climate change will challenge the ocean's ability to meet growing food demands, the ocean could produce more food than it does currently through swift and ambitious action to reduce emissions, reform capture fisheries and expand sustainable mariculture operations.

Sustainably meeting the food demands of a growing and increasingly affluent human population will be one of the greatest challenges of the twenty-first century. The global population is expected to surpass 10 billion people by 2100 (around 3 billion more people than today) with especially high growth in population and food demand expected in Africa[1]. Increasing wealth, particularly in Asia, will further add to growing demands for meat[4]. Land-based food production, including inland fisheries and aquaculture, is vast, growing and crucial to meeting increased food demand, but its expansion is challenged by competing resource demands: livestock and agriculture already occupy more than 40% of habitable land area[5], there is growing demand for land for urban expansion[6], and food production and human consumption compete for limited freshwater resources[7]. Furthermore, the effects of climate change on land-based food systems[8]—exacerbated by their own large greenhouse-gas footprints[9]—threaten their ability to fulfil future meat demands alone.

Despite occupying nearly three-quarters of the world's surface area, the ocean currently provides only 17% of the global meat supply[2,10]. Historically, most seafood has come from wild fish and invertebrates harvested by marine fisheries, although a rapidly increasing proportion comes from species farmed through mariculture[10]. Although seafood production could be expanded by improving fisheries management and expanding sustainable mariculture[2], climate change challenges the efficacy of these actions[3]. Both the productivity of marine fisheries[11,12] and extent of suitable area for mariculture[13,14] are expected to decline as ocean conditions change. Human responses to these changes could mitigate or exacerbate the impacts of these effects on society. Here we investigated whether climate adaptive actions in both ocean food sectors collectively could help to meet the looming food security challenges of this century.

Climate change is altering the distribution and productivity of fish stocks, thus changing where and how much fish can sustainably be caught. Maximizing the catch from marine fisheries will therefore require management that maximizes long-term sustainable catch rates while accounting for climate-driven shifts in productivity[15] and international cooperation to maintain sustainable management as populations shift into new areas[16]. Although such climate-adaptive

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[1]Bren School of Environmental Science and Management, University of California, Santa Barbara, Santa Barbara, CA, USA. [2]Marine Science Institute, University of California, Santa Barbara, Santa Barbara, CA, USA. [3]College of Science and Engineering, James Cook University, Townsville, Queensland, Australia. [4]Environmental Studies, University of California, Santa Barbara, Santa Barbara, CA, USA. [5]Department of Ecology, Evolution, and Marine Biology, University of California, Santa Barbara, Santa Barbara, CA, USA. [6]Oceans Program, Environmental Defense Fund, San Francisco, CA, USA. [7]Future Oceans Lab, CIM-Universidade de Vigo, Vigo, Spain. [8]Environmental Markets Lab, University of California, Santa Barbara, Santa Barbara, CA, USA. [9]The Pew Charitable Trusts, Washington, DC, USA. [10]Arctic Research Center, Hokkaido University, Sapporo, Japan. [11]Graduate School of Environmental Science, Hokkaido University, Sapporo, Japan. [12]Global Station for Arctic Research, Global Institution for Collaborative Research and Education, Hokkaido University, Sapporo, Japan. [13]Department of Environmental Science, Policy, and Management, University of California, Berkeley, CA, USA. [14]Faculty of Economics, University of Iceland, Reykjavík, Iceland. [15]The Marine Science Institute, College of Science, University of the Philippines Diliman, Quezon City, Philippines. [16]Australian Institute of Marine Science, Townsville, Queensland, Australia. [17]Plymouth Marine Laboratory, Plymouth, UK. ✉e-mail: cfree14@gmail.com

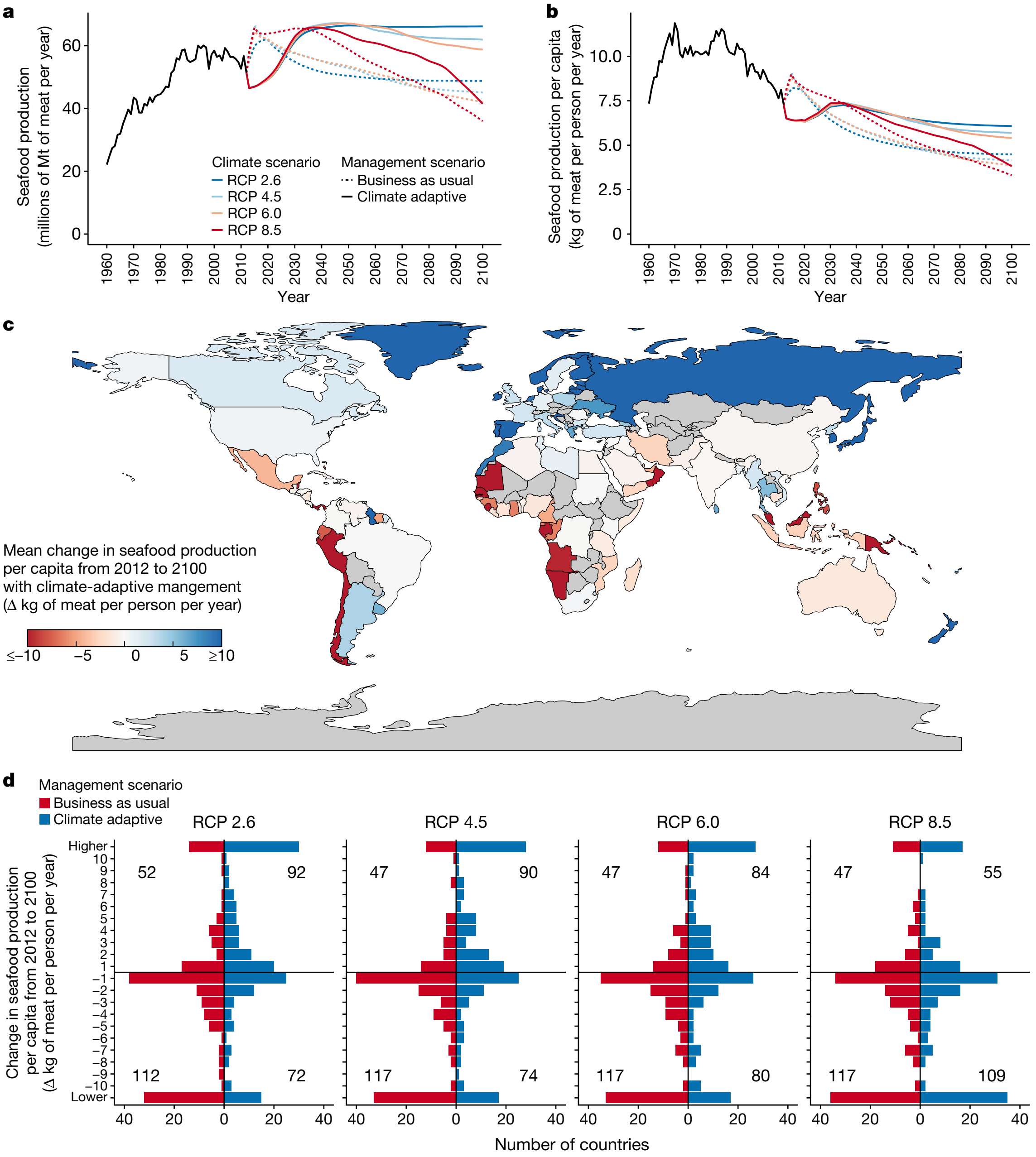

Fig. 1 | Impact of climate change and fisheries management on the production of seafood from marine fisheries. a, **b**, The global change in annual seafood production (**a**) and (**b**) seafood production per capita historically (black lines) and projected under each climate-change and fisheries-management scenario (coloured lines). **c**, The mean country-level change (Δ) in annual seafood production per capita across all four climate-change scenarios assuming climate-adaptive fisheries reforms. Countries in grey are landlocked or uninhabited (such as Antarctica) and do not have marine fisheries. **d**, The number of coastal countries experiencing gains or losses in annual seafood production per capita in each climate-change and fisheries-management scenario. Numbers indicate the number of countries falling in each quadrant ($n = 164$ total).

management reforms could increase global fisheries catch under moderate climate change[17] (Fig. 1a), they are unlikely to maintain catch for all countries, especially low-income nations in the tropics[18]. Although international trade could partially offset declines in domestic fisheries catches, increasing domestic alternatives is critical for supporting local livelihoods, food security, innovation and participation in the global market[19].

Although mariculture production is also challenged by climate change[3,20], it has grown rapidly despite historical environmental changes[10] (Fig. 2a, b) and is well-positioned for continued growth with effective planning and governance. Over the past three decades, the number of mariculture species has increased by 30%, the conversion efficiency of wild fish to farmed fish (that is, the fish in, fish out (FIFO) ratio) has increased exponentially, and production has increased by around 7% annually (Fig. 2a–d). Expanding global mariculture production under climate change will mostly depend on effective governance and planning tools for species and location selection[21], but could be accelerated by innovations in feed[22,23] and selective breeding for fast growth, disease resistance and environmental tolerance[24]. Enhancing domestic mariculture production to meet the increasing local demand will require policies for promoting sustainable mariculture in more countries.

Here we investigated whether coordinated policy, technology and management reforms in marine fisheries and mariculture could increase per capita seafood production under climate change (Representative

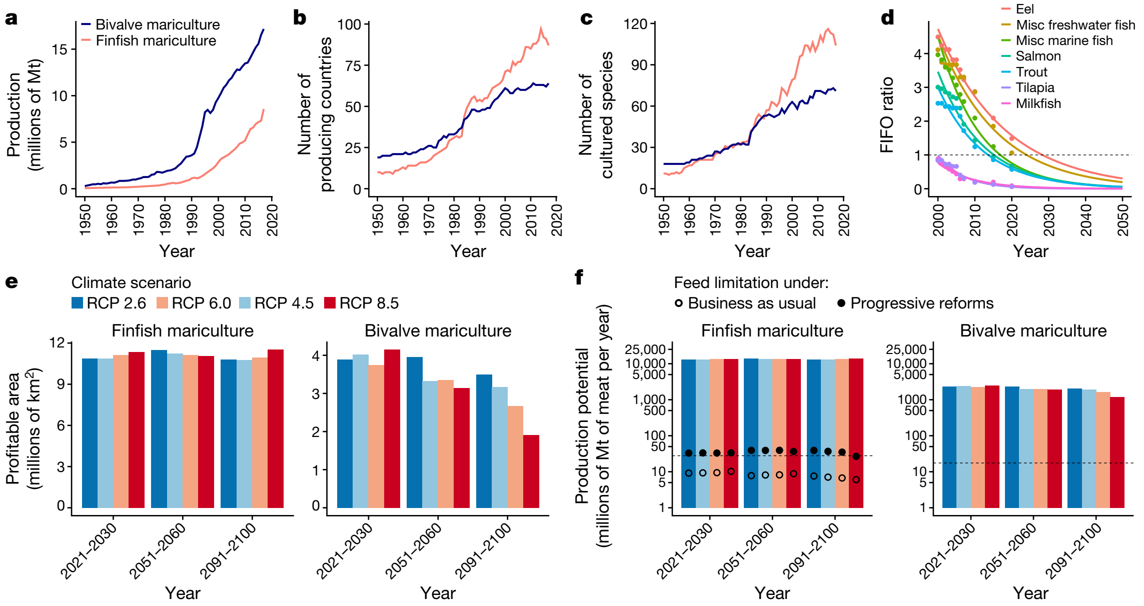

Fig. 2 | Opportunities for the expansion of sustainable mariculture to increase seafood production under climate change. a–d, The technological progress already made towards fostering future mariculture expansion[10]. In **d**, the FIFO ratio represents the amount of wild fish required to produce one unit of farmed fish; ratios below 1 (the dashed horizontal line) indicate the efficient conversion of wild fish into farmed fish[55–57]. Points represent historical values and lines represent projected exponential declines. Misc, miscellaneous. **e**, **f**, The amount of potentially profitable area available for mariculture (**e**) and the annual production potential of this profitable area under climate change (**f**). In **f**, the bars represent the environmental and economic potential for sustainable mariculture if unconstrained by the upper limits of future consumer demand (dotted lines) or the availability of feed from capture fisheries (dots). The upper limits of future consumer demand were estimated to be double the 2050 demand estimated previously[2].

Concentration Pathways (RCPs) 2.6, 4.5, 6.0 and 8.5). We use projections of human population growth[1] and fisheries production under climate change and alternative management responses[18] to show that climate-adaptive fisheries reforms are necessary but insufficient to increase per capita seafood supplies. We then explore the potential for sustainable mariculture to complement fisheries reforms, offset losses in fisheries production and expand per capita seafood supply from a changing ocean. We forecast sustainable mariculture production potential using conservative harvest densities, accounting for the constraints of habitat suitability, competing ocean uses, economic feasibility, feed availability for fed mariculture (which depends on fisheries production) and consumer demand for mariculture products that accounts for the likely growth in supply of and demand for land-based seafood substitutes[25] (Supplementary Tables 1, 2). These projections are not predictions of what will happen: they are explorations of what could happen through large-scale reforms and investments. Overall, we document where fisheries reforms and sustainable mariculture expansion could meet expected domestic growth in demand and highlight gaps that must be filled by other food sectors and international trade.

Climate-adaptive fisheries reforms

A previous study[18] projected climate-driven shifts in the distribution and productivity of 779 harvested marine species and measured outcomes under two fisheries management scenarios: (1) climate-adaptive management, in which economically optimal harvest rates are maintained as stocks shift into new management areas; and (2) business-as-usual management, in which current harvest rates degrade to open access as stocks cross management boundaries. Accounting for an increased demand from a growing human population, we find that climate-adaptive fisheries management reforms will be necessary but insufficient to maintain per capita seafood production under climate change. Although fisheries reforms could increase global seafood production under all but the most severe climate scenario (RCP 8.5) (Fig. 1a), a growing human population means that these increases are unlikely to be sufficient for maintaining per capita seafood production under any climate-change scenario (Fig. 1b). Fisheries management reforms could increase per capita seafood supply in some countries (for example, poleward countries with increasing fisheries productivity and decreasing human populations), but most countries are projected to have less seafood per capita than today (Fig. 1c, d). Losses in per capita seafood supply are projected to be especially large in tropical low-income countries that face the largest declines in fisheries productivity and the greatest human population growth (Fig. 1c). Although fisheries management reforms alone cannot increase global or national per capita seafood supplies, they generate far better outcomes than business-as-usual management (Fig. 1a, b, d). Climate-adaptive fisheries reforms are therefore important to minimize the seafood deficit left for domestic mariculture or international trade to fill and to maximize the livelihood and cultural value of capture fisheries.

Climate-adaptive mariculture expansion

The potential for sustainable mariculture to offset climate-driven losses in seafood from fisheries depends on sustainable practices, habitat suitability, economic feasibility, feed availability and technology, and consumer demand. We modelled this potential assuming low-impact harvest densities: finfish farms use densities consistent with European organic standards[26] and bivalve farms use precautionary densities equal to half of California's guidelines[21]. We mapped suitable areas for 122 finfish and 22 bivalve mariculture species (Supplementary Data) in 2021–2030, 2051–2060, and 2091–2100 under climate change, excluding areas with existing uses (that is, marine protected areas, shipping lanes and oil development), disputed ownership, or in waters for which the depths, wave intensities or current velocities are unsuitable for profitable mariculture development. We calculated production potential and profitability of suitable areas using species-specific growth rates and production costs (that is, capital costs of vessels and equipment and operating costs of maintenance, wages, fuel, feed and insurance) and excluded unprofitable areas from

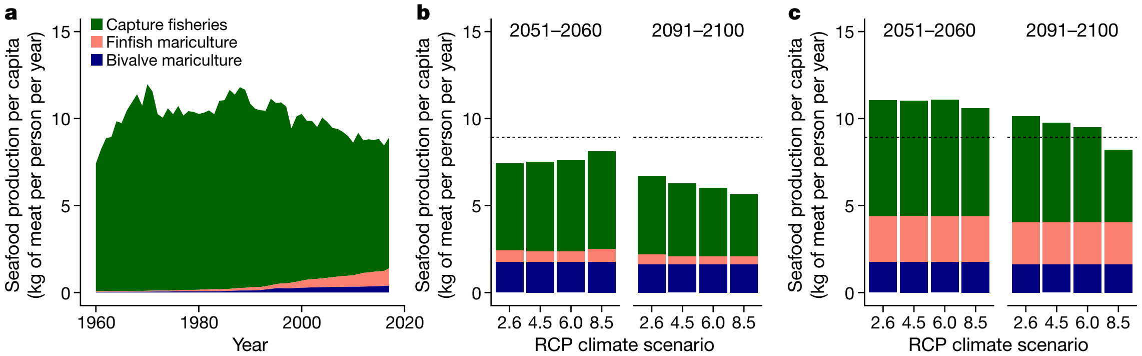

Fig. 3 | Global seafood production per capita from marine fisheries and mariculture. a–c, Historical production per capita[10,58] (**a**) and potential future production per capita under climate change in the business-as-usual scenario (**b**) or with progressive reforms in fisheries and mariculture policies (**c**). In **b** and **c**, dashed lines indicate the current seafood production per capita. Business-as-usual fisheries management assumes that current harvest rates degrade as populations shift into new management areas whereas reformed fisheries management assumes that economically optimal harvest rates are maintained as populations shift into new management areas. Business-as-usual finfish mariculture policies assume moderate advances in fish in, fish out ratios (values projected for 2030; see Fig. 2d) whereas reformed finfish mariculture policies assume substantial advances in FIFO ratios (values projected for 2050; see Fig. 2d). Bivalve mariculture is the same in both policy scenarios.

development. For finfish mariculture, which is fed with feed partially derived from wild forage fish (such as herring, anchovy, sardine and menhaden), we also constrained production potential on the basis of forage fish availability and conversion efficiency under two policy scenarios: (1) a business-as-usual scenario that assumes business-as-usual fisheries management (Fig. 1a) and moderate advances in feed technology (2030 FIFO ratios, 0.01–0.91; Fig. 2d) and (2) a progressive reforms scenario that assumes climate-adaptive fisheries management (Fig. 1a) and substantial advances in feed technology (2050 FIFO ratios, 0.001–0.30; Fig. 2d). Finally, we capped production of finfish and bivalve mariculture using estimated upper limits of consumer demand (2050 demand doubled)[2].

The potential to expand sustainable mariculture is vast and production is projected to be limited by consumer demand or feed availability rather than by climate change (Fig. 2e, f). With effective species and location selection, we found that the availability of area for profitable finfish mariculture is insensitive to changes in temperature, oxygenation and salinity (Fig. 2e). Thus, the potential for finfish mariculture is projected to be limited by feed availability and consumer demand rather than by climate-driven losses in profitable areas for development (Fig. 2f). Conversely, we found the availability of area for profitable bivalve mariculture to decrease with increasingly severe climate change, mostly because of ocean acidification (Fig. 2e). However, expansion is not projected to be limited by future ocean conditions since consumer demand can be met under all climate-change scenarios (Fig. 2f). Expanding these results to consider the effects of harmful algal blooms, disease, multiplicative stressors and other factors not directly accounted for in this analysis is a crucial area for future research.

The ability for sustainable mariculture to increase seafood production per capita is not possible without both reforms in fisheries management and technological innovations in fed mariculture. Business-as-usual fisheries management and advances in mariculture feed technology did not allow mariculture expansion to meet consumer demand for finfish mariculture (Fig. 2f) because of the limited supply of forage fish from fisheries and inefficient conversion of forage fish into farmed fish. Thus, business-as-usual fisheries and mariculture practices are unlikely to maintain global seafood production per capita under any climate-change scenario (Fig. 3b). Outcomes worsen with increasingly severe climate change (Fig. 3b) as food and feed production from fisheries decline (Fig. 1a) and finfish mariculture becomes more feed limited (Fig. 2f). By contrast, climate-adaptive fisheries reforms and innovation in mariculture feed allowed mariculture production to expand until it was demand limited rather than feed limited under every climate-change scenario (Fig. 2f). As a result, reforms in fisheries management and advances in mariculture technology could increase per capita global seafood production under all but the most severe climate-change scenario (Fig. 3c).

To assess the ability of coastal countries to avoid domestic seafood deficits by reforming fisheries and expanding sustainable mariculture, we modelled four development scenarios. When mariculture expansion was limited to existing producers (bivalves, 71 countries; finfish, 91 countries) in proportion to current global production (current development), 57–66% of coastal countries (RCP 8.5–2.6, here and below) increased per capita seafood production (Fig. 4a). When mariculture expansion occurred in proportion to 2100 human population sizes (proportional development), 76–83% of coastal countries increased per capita seafood production (Fig. 4a). When mariculture expansion occurred only in countries for which per capita production from fisheries decreased (offset-based development), 74–76% of coastal countries increased per capita seafood production (Fig. 4a). Finally, when mariculture expansion was optimized to maintain per capita seafood supplies (optimal development), 87–91% of coastal countries increased per capita seafood production. Thus, avoiding domestic seafood deficits may be possible in most coastal countries, but will depend on which countries prioritize investment in fisheries reforms and sustainable mariculture expansion.

Increasing mariculture production is expected to reduce prices, increase affordability and increase consumption of seafood in every nation[27]. However, reduced prices and increased operational costs due to climate-change-associated effects (such as more disease or more harmful algal blooms) could reduce the profitability and production potential of mariculture. Our results were robust to a sensitivity analysis in which prices were 30% lower than today and costs were 30% higher than predicted by the model (Extended Data Figs. 1–3). However, in our model, mariculture did not increase per capita seafood production when costs more than doubled (around 2.3×) today's costs. Furthermore, increasing per capita seafood production became increasingly challenging in scenarios with higher human population growth (Extended Data Figs. 4, 5). We qualitatively explore the sensitivity of our projections to additional model assumptions and uncertainties in Supplementary Table 3.

Expanding sustainable mariculture

Expanding sustainable mariculture will require policies that define and support sustainable mariculture development in more places.

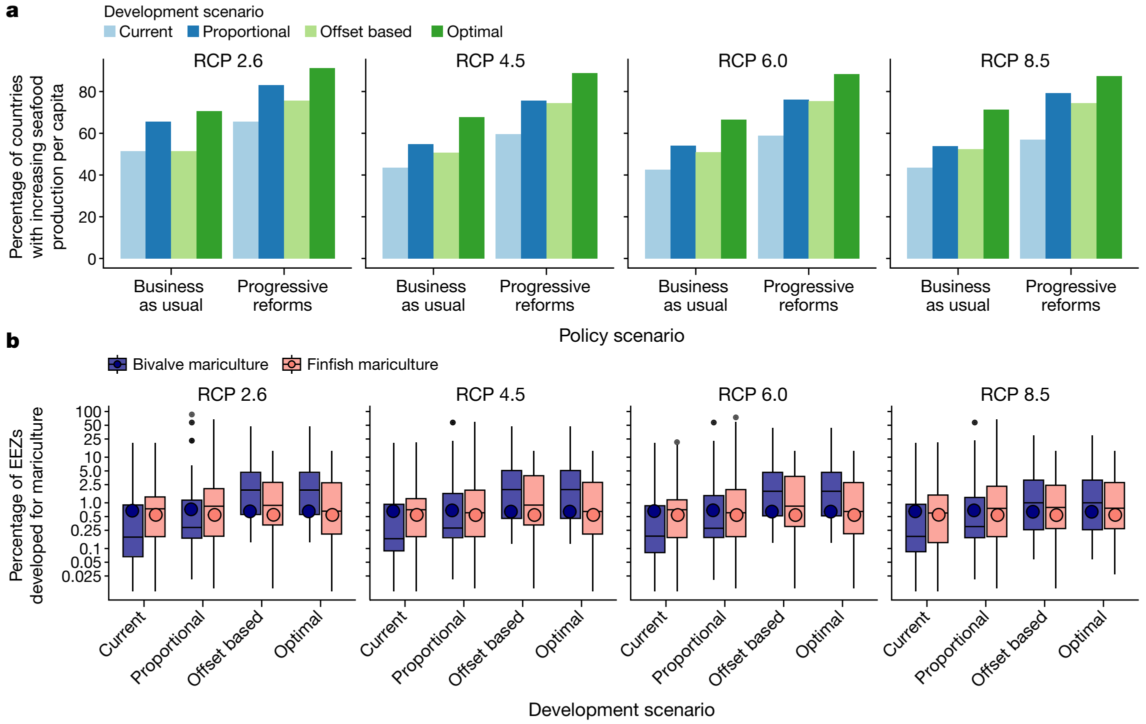

Fig. 4 | National seafood production trends and mariculture production footprints under different mariculture-development scenarios. a, the percentage of coastal countries ($n = 164$ countries) with increasing seafood production per capita from 2017 to 2091–2100 with progressive reforms in marine fisheries and mariculture under climate-change and mariculture-development scenarios. **b**, The percentage of exclusive economic zones (EEZs) ($n = 164$ countries) that would be developed for mariculture in 2091–2100 under each climate-change and mariculture-development scenario. Box plots show the distribution of development percentages among countries and circles show the percentage of EEZs developed globally. High percentages occur in countries with very small EEZs (for example, Belgium). In the box plots, the solid line indicates the median, the box indicates the interquartile range (25th to 75th percentiles), the whiskers indicate 1.5× the interquartile range and the dots beyond the whiskers indicate outliers. The current development scenario assumes that countries develop mariculture in proportion to current production levels; the proportional development scenario assumes that countries develop mariculture in proportion to their projected 2100 population size; the offset-based development scenario assumes that only countries losing seafood per capita from fisheries develop mariculture; and the optimal development scenario assumes that mariculture development is optimized to maintain seafood production per capita for the maximum number of countries.

In highly regulated regions, poorly defined and convoluted regulations can suppress mariculture growth[28], and expansion will require clearly defined best practices and standardized permitting procedures. In weakly regulated regions, relaxed standards have resulted in ecosystem degradation and inefficient mariculture production[28], and expansion will require more-effective regulatory oversight. In countries with no or limited historical production, investment in technical training, supply chain infrastructure, and local governance will be necessary to stimulate mariculture development. The space required for mariculture to meet consumer demand is small (rarely more than 3% of a country's exclusive economic zone in the modelled development scenarios; Fig. 4b), and participatory planning tools can be used to minimize any negative impacts on local ecosystems and human communities[21], and to promote ecosystem services including coastal protection, nutrient remediation and habitat production[29]. Integrated multi-trophic aquaculture also presents opportunities to reduce spatial requirements, increase productivity, reduce disease risk and minimize environmental impacts[30].

Expanding sustainable finfish mariculture will require improvements in the availability, efficiency and affordability of feed at a global scale. These improvements could be achieved by: (1) increasing the quantity of raw material available for reduction (for example, fishmeal and fish oil production) through fisheries reforms or by targeting new fisheries or fish by-products for reduction; (2) directing more marine fish ingredients to mariculture (21% today) by reducing marine fish ingredients in feed for freshwater aquaculture (53% today) or terrestrial agriculture (25% today)[31]; (3) continuing to replace marine fish ingredients with macroalgae[32], land-based alternatives or emerging technologies with even lower environmental impacts[22]; and (4) increasing feed conversion rates through better husbandry or selective breeding[33]. Innovations in feed composition and husbandry have already reduced reliance on wild fisheries considerably (Fig. 2d). Most of the protein in feed now comes from terrestrial crops, such as soy and maize (corn)[34], and more nutritious and sustainable sources of protein (such as algae, insects and yeast) are being developed and incorporated into feed as technologies improve and production costs decline[22,23]. Paradoxically, shifting the source of mariculture feed to land could decrease the land footprint of global food production[34]. Because feed conversion ratios are much higher for mariculture than for livestock, shifts in consumer preferences away from terrestrial meat could reduce the land footprint required for terrestrial agriculture[34].

In many locations, expanding sustainable mariculture operations will require increasing their resilience to adverse climate-change impacts. This could be achieved using marine spatial planning to locate mariculculture in areas of minimal risk[35] and by improving access to credit and insurance to buffer operators against environmental risk and uncertainty[36]. Furthermore, although terrestrial crops and livestock have been selectively bred for centuries[37], fewer than 10% of mariculture species have undergone selective breeding[38]. Breeding a greater proportion of maricultured organisms for fast growth[24], disease resistance[39] and/or environmental tolerance[40] could offset several negative effects of climate change[41] and even reduce impacts on the environment[33].

Production in low-income countries

Many fisheries in tropical low-income countries are overfished and vulnerable to climate change. In these locations, implementing climate-adaptive fisheries reforms could improve seafood availability, enhance fishery sustainability and facilitate the expansion of mariculture by providing a local supply of feed, fingerlings or spat. Collectively, these improvements could enhance food, nutrition and livelihood security[27]. Enabling sustainable and equitable mariculture expansion in many of these communities may require transformation rather than adaptation. It will probably also require clear and effective governance, as well as investments in (1) technology and knowledge transfer to reduce dependency on wild stocks for seed and feed; (2) innovations that address unique geographical vulnerabilities and constraints (for example, culturing native species adapted to local hazards and developing mariculture operations that minimize trade-offs with sensitive habitats such as mangroves and coral reefs); (3) capacity building and learning networks to improve initial outcomes and promote in-region knowledge sharing; (4) data systems and knowledge management to facilitate marine spatial planning; and (5) policies and institutions that minimize barriers to entry (such as financial, legal and risk barriers) and promote community participation and ownership[42]. Promoting participation across economic, ethnic, racial and gender dimensions could also address or lessen the socioeconomic impacts of climate change. Importantly, increasing seafood production is expected to reduce prices and increase the affordability of local, sustainable and nutritious food[27].

Conclusions

The ability for fisheries reforms and mariculture expansion to increase seafood production depends on urgent mitigation of greenhouse-gas emissions: even progressive reforms in fisheries and mariculture will not maintain global seafood production per capita under the most severe emissions scenario (Fig. 3c), and reforms will be increasingly challenging to implement with worsening climate change. Furthermore, the disproportionate effects of climate change on tropical low-income countries (Fig. 1c) could exacerbate existing socioeconomic inequities[43]. Finally, emissions reductions are necessary to avoid climate impacts not considered in our model projections. For example, we do not explicitly account for potential increases in storm frequency and intensity, sea-level rise, harmful algal blooms or disease[3], which are likely to increase the costs and decrease the feasibility of fisheries and mariculture operations in many locations[20] (although we assume precautionary mariculture designs—including conservative stocking densities and payment for insurance programmes—aimed to prevent many of these effects). The surest way to avoid these risks and secure the benefits of fisheries reforms and mariculture expansion is to dramatically cut greenhouse-gas emissions[44].

The reforms outlined here are ambitious but achievable and present a platform for making important contributions towards meeting the UN Sustainable Development Goals[45] targeting hunger, nutrition, economic growth, sustainable consumption and healthy oceans, among others. Already, improved management of more than half of global fisheries catch has prompted the rebuilding of overexploited resources[46], conferring greater resilience to climate change[47] and maximizing long-term catch possibilities and profits from fisheries[48]. However, these successes, which have occurred predominantly in high-income countries, must be replicated in more low-income countries to truly contribute to the UN Sustainable Development Goals[46,49]. Rapid accelerations in data-collection and sharing technologies[50] have advanced the development of operational climate forecasting[51], dynamic management[52] and risk planning tools[21]. Furthermore, mariculture practices continue to become more economical and to have lower environmental impacts through industry-driven innovations, better management practices and improved policy support[53]. Notably, the vast area available for mariculture[54] and comparatively small area required to meet consumer demand leaves space for optimizing mariculture design, placement and services around diverse societal values and needs[21]. With effective governance and widespread commitments to expand sustainable mariculture, the ocean can continue to make important contributions to food demand, even under climate change.

Online content

Any methods, additional references, Nature Research reporting summaries, source data, extended data, supplementary information, acknowledgements, peer review information; details of author contributions and competing interests; and statements of data and code availability are available at https://doi.org/10.1038/s41586-022-04674-5.

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Methods

Overview

We combined projections of human population growth[1], marine fisheries production[18] and mariculture production to investigate 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 previously published climate-linked bioeconomic model results[18] and present production outcomes under two fisheries management scenarios (Supplementary Tables 5, 6): (1) business-as-usual 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 habitat suitability, competing ocean uses, economic feasibility, availability of feed for fed-mariculture (which depends on fisheries production) and consumer demand[25] (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 on the basis of business-as-usual 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 on the basis of 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[59], we converted fisheries landings and mariculture production from their live-weight values to their edible meat equivalents using group-level conversion factors[60] (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[61] and all code is available here: https://github.com/cfree14/aquacast.

Marine fisheries analysis

We used a previously published climate-linked fisheries bioeconomic model[18] 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 and 8.5; Supplementary Table 4) and two fisheries management scenarios from 2012 to 2100. The previous study[18] evaluated 779 harvested marine fish and invertebrates, the initial distributions of which were determined using AquaMaps[62] and for which the initial biomasses, fishing mortalities and statuses (B/B_{MSY}) were determined on the basis of previous research[48]. The changes in distribution and productivity were then projected using the following general procedure: (1) distributions were updated using a bioclimatic envelope model[63]; (2) productivity was assumed to change in proportion to changes in range size, that is, a 10% increase in range size results in a 10% increase in productivity (a detailed justification of this assumption was published previously[17]); and (3) biomass, catch and profits were updated on the basis of an updated version of the previously published bioeconomic model[48] and the selected management scenario. 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 previously[18], we considered two here: (1) business-as-usual (that is, no adaptation) and (2) climate-adaptive fisheries management (that is, full adaptation). Climate-adaptive fisheries management adapts to 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 ref. [18] for further details). Range shift adaptations result from international cooperation that effectively maintains management as stocks shift into new management areas. Business-as-usual fisheries management does not implement either adaptation (Supplementary Tables 5, 6): it maintains current (and often suboptimal) harvest rates for species that do not shift spatially, whereas management degrades to open access for stocks that shift into new management areas.

The previous analysis[18] considered only species-specific stocks described in the FAO Landings Database[10] (that is, it excludes 'not elsewhere included' stocks and stocks with catch reported at the class, order, family and genus levels) and therefore includes 59% of the 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 the total reported landings in the FAO Landings Database. This assumes that landings from the excluded (non-species-specific) stocks change proportionally to the effects of climate change and management on the included (species-specific) stocks. We assume that 18% of landings are directed to reduction (that is, the processing of wild fish into fish oil and fishmeal) as reported previously[64]. 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 previously published conversion factors[60] (Supplementary Table 8) and calculated global and coastal country-level edible meat per capita using population projections from UN-DESA[1].

Mariculture analysis

Overview. We forecast the sustainable mariculture production potential of 122 finfish and 22 bivalve species in 2021–2030, 2051–2060 and 2091–2100 under four climate scenarios (RCPs 2.6, 4.5, 6.0 and 8.5; Supplementary Table 4) while accounting for the joint constraints of habitat suitability, competing ocean uses, economic feasibility, availability of feed for fed mariculture and consumer demand[25] (Supplementary Tables 1, 2). In each year, we mapped the suitability of a 10 km × 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 suitable habitat. We excluded suitable cells with existing uses (that is, marine protected areas, high-density shipping lanes and oil development) and in waters with depths, wave intensities and current velocities that are 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, time to harvest 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 by the availability of feed from capture fisheries (which is determined using the capture fisheries scenarios described above). When necessary, we capped the production potential for finfish (32 million and 28 million Mt of total and meat production) and bivalve (103 million and 18 million Mt of total and meat production) mariculture at the estimated upper limits of consumer demand (2050 demand doubled)[2].

Species selection and data collection. We identified 122 finfish and 22 bivalves mariculture species currently under production[10] or under consideration for production[65] (Supplementary Fig. 2) with the life-history parameters and environmental tolerances required for this analysis. We collected the required species-specific growth and mortality parameters using FishLife[66], FishBase[67], SeaLifeBase[68] and literature values (Supplementary Figs. 3, 4). Life-history parameters represent averages across a species' range and do not vary by location or environment. We used the minimum and maximum values in AquaMaps occurrence data[62] to characterize species' temperature and salinity tolerances (Supplementary Fig. 5). Additionally, we derived the size at harvest using the FAO Cultured Aquatic Species Fact Sheets[69] (Supplementary Figs. 6, 7), FIFO ratios using previously published feed conversion rates (FCRs)[56], previously published feed compositions[57] (Supplementary Fig. 8 and Supplementary Table 7), and prices from FAO aquaculture production price data[10] (Supplementary Fig. 9). See Supplementary Information for more details on species selection, data collection and parameter derivation.

Estimating the production potential. Identifying suitable areas. We projected suitable areas for mariculture development under four 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[70,71] and previously published wave-height projections[72]. The GFDL-ESM2G model provides monthly gridded outputs with a resolution of 1° longitude and 0.375–0.5° latitude (lower resolution at the poles). We mapped habitat suitability for the production of each mariculture species on a 10 km × 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, 10). We assumed that mariculture species can be cultivated only 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 previously published specifications[73] and assumed that finfish and bivalve species can be cultivated only in areas with annual average dissolved oxygen concentrations above 4.41 mg l^{-1} (0.28 mol m^{-3}) and 1.99 mg l^{-1} (0.12 mol m^{-3}), respectively. Detailed derivations and justifications of these environmental limits are provided in the original references[72,73]. We assumed that bivalve mariculture can occur only 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 previously published studies[13,73] (Supplementary Fig. 10). We assumed that bivalve species can be cultivated only in areas with average annual aragonite saturation (Ω) greater than 1.75 (Supplementary Fig. 11). This threshold is slightly higher than the 'break-even' point ($\Omega = 1.70$) for viable commercial mariculture for Pacific oysters (*Magallana gigas*) at a shellfish hatchery in Washington, USA[74]. 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 (Supplementary Table 11) and with annual maximum current speeds less than 1.0 m s^{-1} (ref. [75]) (Supplementary Table 9). Furthermore, we assumed that mariculture will occur only in areas with annual average current speeds greater than 0.04 m s^{-1} to minimize negative environmental impacts from finfish mariculture and to ensure sufficient flow for bivalve mariculture[75]. We assumed that mariculture will occur only in undisputed EEZs because of 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 (for example, Clipperton, Heard/McDonald Islands, Pitcairn and Wake Islands) (Supplementary Table 12 and Supplementary Fig. 12) and areas currently being used as marine protected areas, high-density shipping lanes or offshore oil development (Supplementary Fig. 13).

Estimating the biological production potential. We calculated the production potential in each suitable cell on the basis of sustainable farm designs (Supplementary Table 13 and Supplementary Fig. 14), sizes at harvest and the time required to reach harvest sizes. Each square kilometre of finfish farm was assumed to contain 20 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[26]. For bivalve mariculture, we conservatively assume a maximum harvest density of 1,500 Mt km^{-2}, which is approximately half the density used by US shellfish growers[21]. 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 643 m of fuzzy rope[21] and a density of 400 cm of bivalves per foot (0.3 m) of rope at the time of harvest[73]. 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:

$$N_o = \frac{N_t}{e^{-Mt}} \qquad (1)$$

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

$$W_s = a_s L_s^{\,b_s} \qquad (2)$$

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

$$T_s = -\log(1 - L_s/L_{\mathrm{inf},s})/K_s \qquad (3)$$

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

$$P_s = \frac{N_s W_s}{T_s} \times 100 \text{ farms} \qquad (4)$$

where N_s is the number of stocked juveniles. This value is converted to metric tonnes per year. Supplementary Figure 15 shows the distribution of annual production potential by the International Standard Statistical Classification of Aquatic Animals and Plants.

Constraining production potential by economic feasibility. We assumed that mariculture will only occur where it is profitable (that is, profits greater than zero). We calculated the annual profitability of a cell as the annual revenues minus the annual costs. The annual revenue (US\$ per year) of a cell developed for species s is the product of the productivity of the cell (Mt per year) and the price of species s (US\$ per 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 (that is, cages, lines and feed gear) and the annual operating costs associated with labour, fuel, feed, insurance, and vessel and equipment maintenance (Supplementary Tables 15–17). We amortized capital costs assuming a 10% discount rate and 10-year pay-off period. We calculated labour costs assuming that each 1 km^2 farm employs eight workers who are compensated for a 40-h week plus transit time[21]. Workers were compensated using country-level median wages from the World Bank[76] (Supplementary Figs. 16, 17). We calculated fuel costs on the basis of the previously published mariculture vessel specifications (for example, number, speed and efficiency of vessels)[21], the distance of the farm from the shore and country-level median diesel costs from the World Bank[77] (Supplementary Figs. 16, 17). We obtained the World Bank development indicators using the wbstats R package[78]. We calculated the cost of annual feed demand as the product of the productivity of the cell (Mt per year), the FCR (Mt of feed per Mt of production), and the price of feed (US$ per Mt). The cost of vessels, equipment, vessel and equipment maintenance, insurance and other annual operating costs were based on previously published studies[21,79]. See Supplementary Tables 15–17 for cost parameters and sources.

Constraining by feed availability and consumer demand. The potential for fed mariculture is limited by the availability of feed ingredients derived from wild capture fisheries[31] but this limitation could be reduced through increases in the availability of feed or the efficiency with which feed is converted to farmed fish (Supplementary Table 18). 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 scenario that assumes business-as-usual fisheries management (Fig. 1a and Supplementary Fig. 18) and moderate advances in feed technology (FIFO ratios projected for 2030, 0.01–0.91; Fig. 2d and Supplementary Fig. 19) and (2) a progressive reforms scenario that assumes climate-adaptive fisheries management (Fig. 1a and Supplementary Fig. 18) and progressive advances in feed technology (FIFO ratios projected for 2050, 0.001–0.30; Fig. 2d and Supplementary Fig. 19). We projected future FIFO ratios assuming a continued exponential decline in the FIFO ratios reconstructed through analysis of trends in FCRs[56] and feed compositions (fishmeal and fish oil percentages)[57] (Supplementary Figs. 8, 19). See equation (5) 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[56] (Supplementary Fig. 8). We also assume no change in the proportion of global landings used for reduction (that is, processing of wild fish into fishmeal and fish oil) (18% currently[64]) or the proportion of reduction-destined landings directed to mariculture feed (21% currently[31]).

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 FIFO ratio ($FIFO_s$) for species *s*:

$$FF_{p,s} = AQ_{p,s} FIFO_s \tag{5}$$

where the FIFO ratio is derived for each feed group in each feed scenario using the following equation as previously described[55]:

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

where the FCR and percentage of fishmeal (FM) and fish oil (FO) in feed vary based on feed group and technology scenario (Supplementary Table 7 and Supplementary Figs. 8, 19) and the yields of fishmeal and fish oil from forage fish are fixed at 22.4% and 4.85%, respectively[80]. 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) optimal 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 occur only 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 optimal development scenario, mariculture development is optimized to maintain seafood production per capita for the maximum number of countries. In all four scenarios, countries use their production allocation by developing the most profitable cells first.

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 because of increased seafood supply[27] and costs may be higher because of uncertainty in the cost model or climate-change impacts not directly accounted for in our model (such as storms, disease and harmful algal blooms).

Reporting summary

Further information on research design is available in the Nature Research Reporting Summary linked to this paper.

Data availability

The data that support this study are available on GitHub (https://github.com/cfree14/aquacast).

Code availability

The codes that support this study are available on GitHub (https://github.com/cfree14/aquacast).

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Acknowledgements We thank Z. Song for sharing the wave-height data. This research is adapted from a Blue Paper commissioned by the High Level Panel for a Sustainable Ocean Economy entitled 'The Expected Impacts of Climate Change on the Ocean Economy'. This research was funded by the High Level Panel for a Sustainable Ocean Economy, Food and Land Use Coalition, and Environmental Defense Fund. E.O. was funded by the European Research Council project CLOCK (GA. 679812) and GAIN-Xunta de Galicia Oportunius programme. The results, conclusions and opinions expressed are those of the authors and do not necessarily reflect the views of their respective organizations.

Author contributions S.D.G., C.M.F., R.B.C., K.F. and C.T. conceived the study. C.M.F., R.B.C., S.D.G., E.O., H.E.F., K.F. and C.T. contributed to the study design. C.M.F., R.B.C., J.E.P., H.E.F., J.G.M., K.J.S., S.D.G., W.B., K.F., M.A.J.-M. and R.A. contributed to the acquisition and analysis of data. C.M.F., R.B.C., S.D.G., W.B., E.O., E.O'R., J.E.P., H.E.F., J.G.M., K.J.S., K.F., C.T., M.A.J.-M. and R.A. contributed to the interpretation of results. C.M.F., R.B.C., S.D.G., W.B., E.O., E.O'R., J.E.P., H.E.F., J.G.M., K.J.S., K.F., C.T., M.A.J.-M. and R.A. wrote and edited the manuscript.

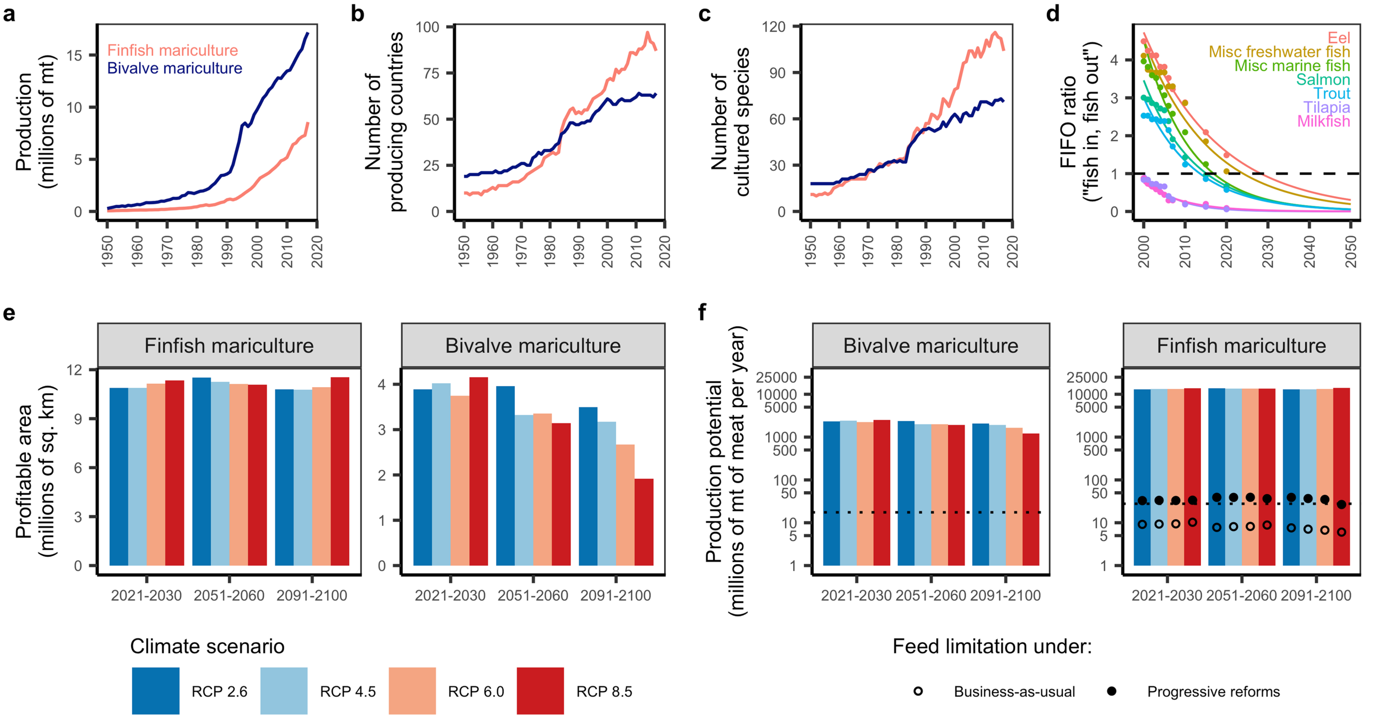
Competing interests S.D.G. is a trustee of the National Marine Sanctuary Foundation, Rare, Resources Legacy Fund and COMPASS. H.E.F. sits on the Technical Advisory Group for the Aquaculture Stewardship Council. All other authors declare no competing interests.

Additional information

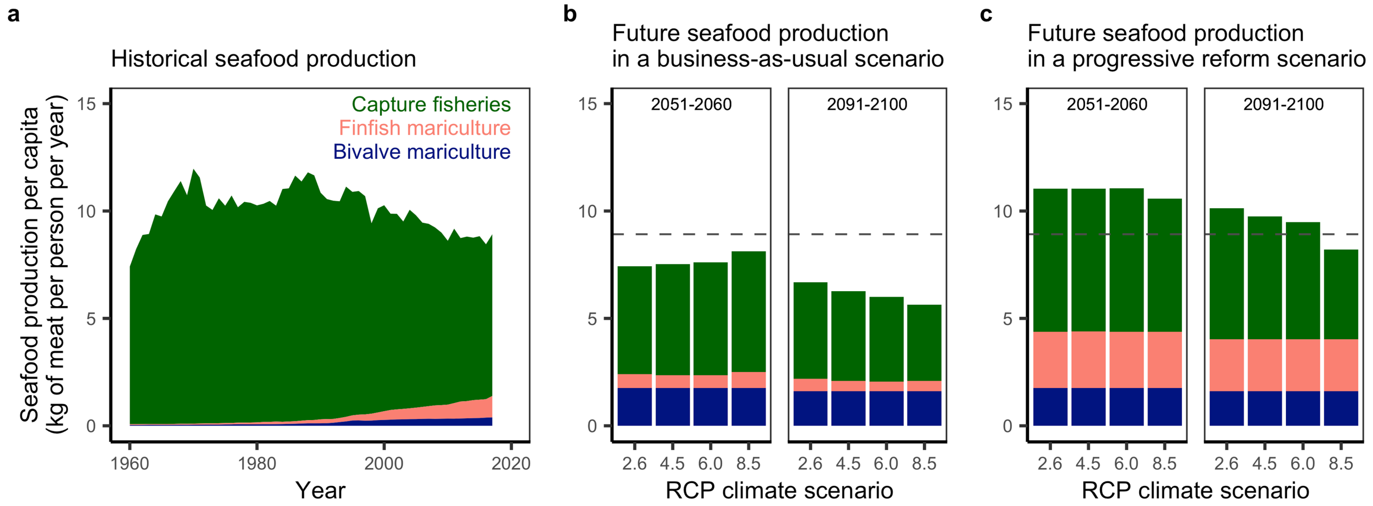
Supplementary information The online version contains supplementary material available at https://doi.org/10.1038/s41586-022-04674-5.

Correspondence and requests for materials should be addressed to Christopher M. Free.

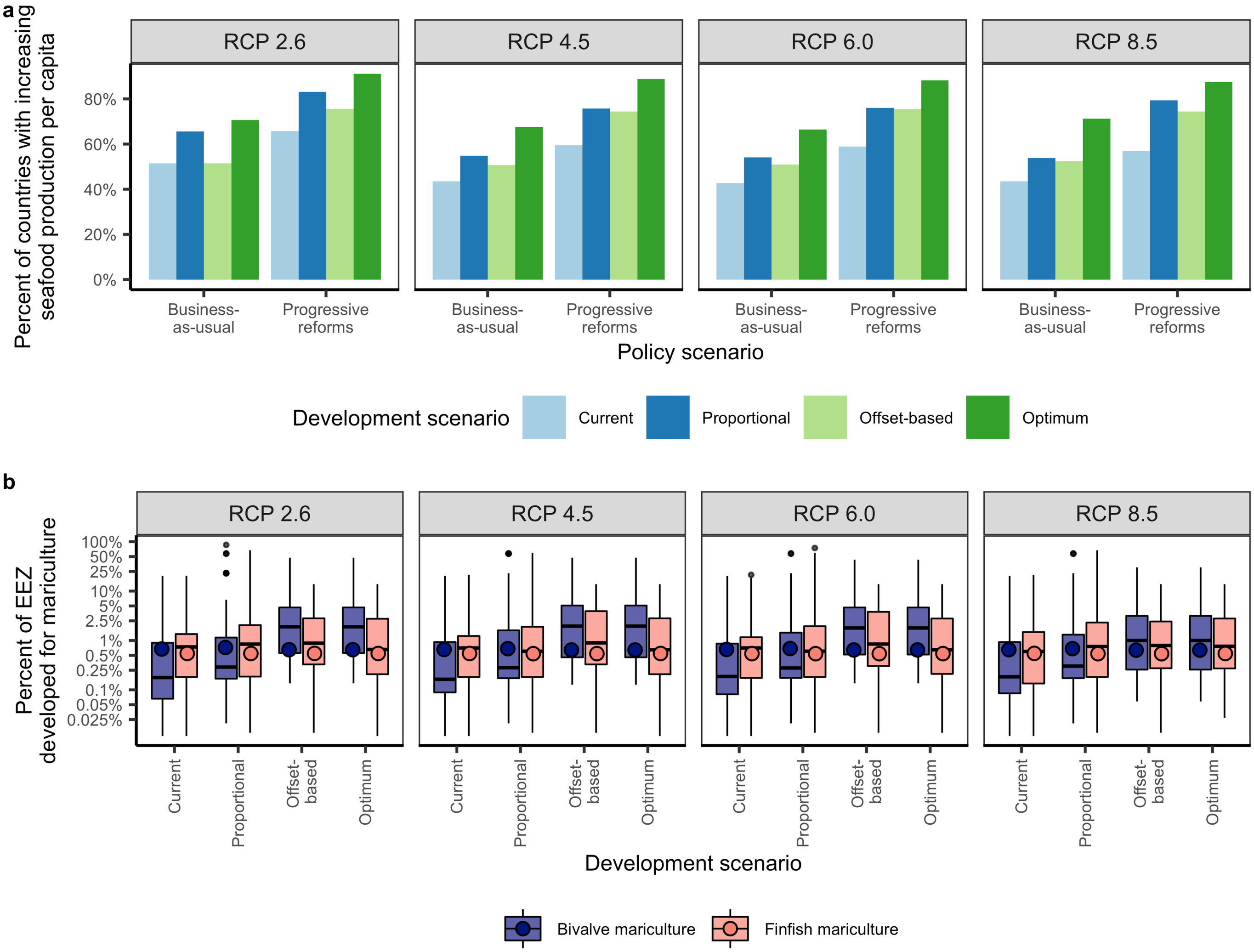
Peer review information *Nature* thanks Kevern Cochrane, Simon Donner, Elizabeth Fulton, Alex Sen Gupta, U. Rashid Sumaila and the other, anonymous, reviewer(s) for their contribution to the peer review of this work. Peer reviewer reports are available.



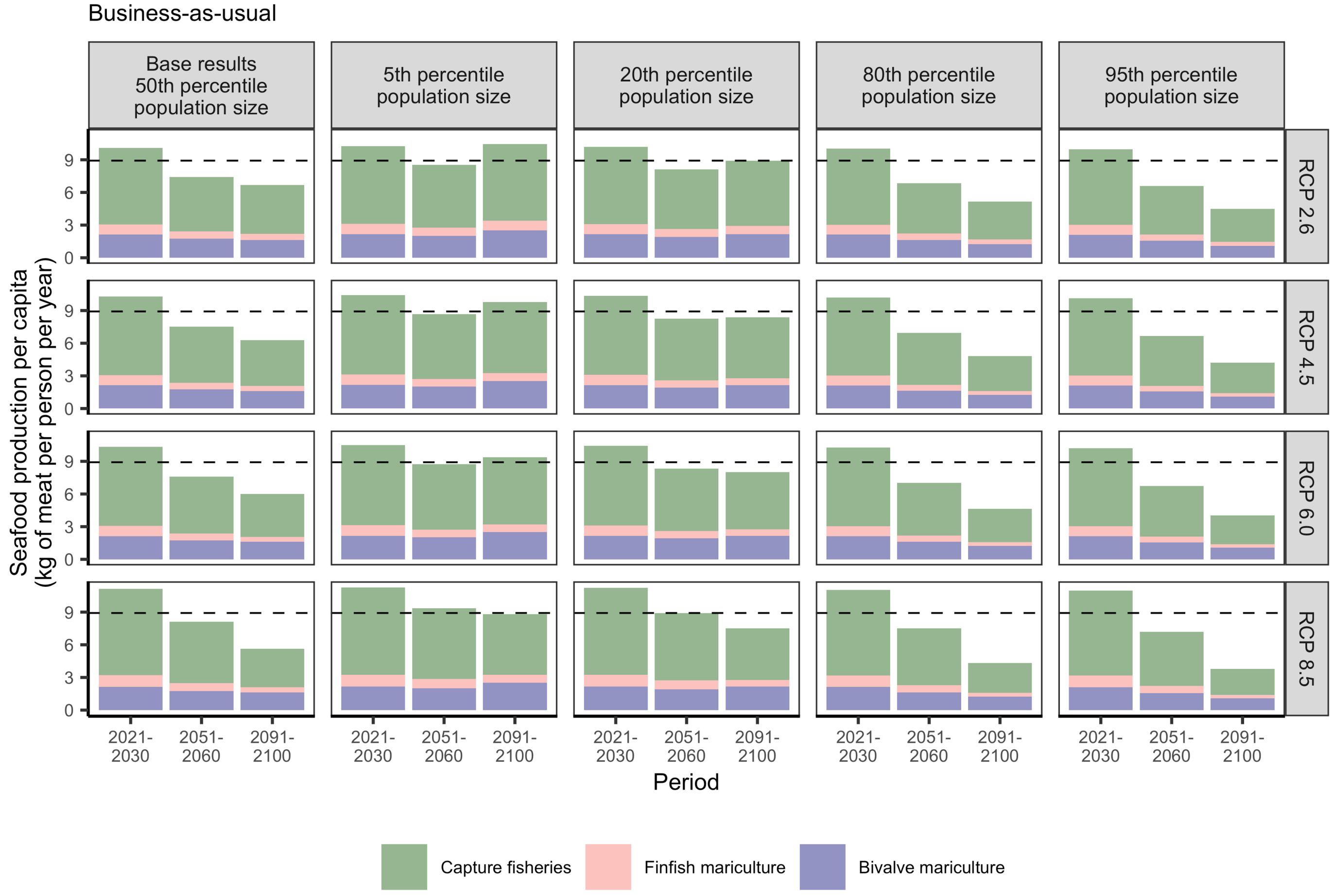
Extended Data Fig. 1 | Opportunities for the expansion of sustainable mariculture to increase seafood production under climate change in the price and cost sensitivity analysis. In this analysis, mariculture seafood prices are 30% lower and mariculture operation costs are 30% higher than in our base scenario. The top row (**a**–**d**) illustrates the technological progress already made towards fostering future mariculture expansion[48]. In (**d**), the FIFO ("fish in, fish out") ratio represents the amount of wild fish required to produce one unit of farmed fish; ratios below one (the dashed horizontal line) indicate the efficient conversion of wild fish into farmed fish[23,24,41]. Points represent historical values and lines represent projected exponential declines. The bottom row shows the (**e**) amount of potentially profitable area available for mariculture and the (**f**) annual production potential of this profitable area under climate change. In (**f**), bars represent the environmental and economic potential for sustainable mariculture if unconstrained by the upper limits of future consumer demand (dotted lines) or the availability of feed from capture fisheries (points). The upper limits of future consumer demand were estimated to be double the 2050 demand estimated by Costello et al[14]. Note the log-scale y-axis in (**f**).



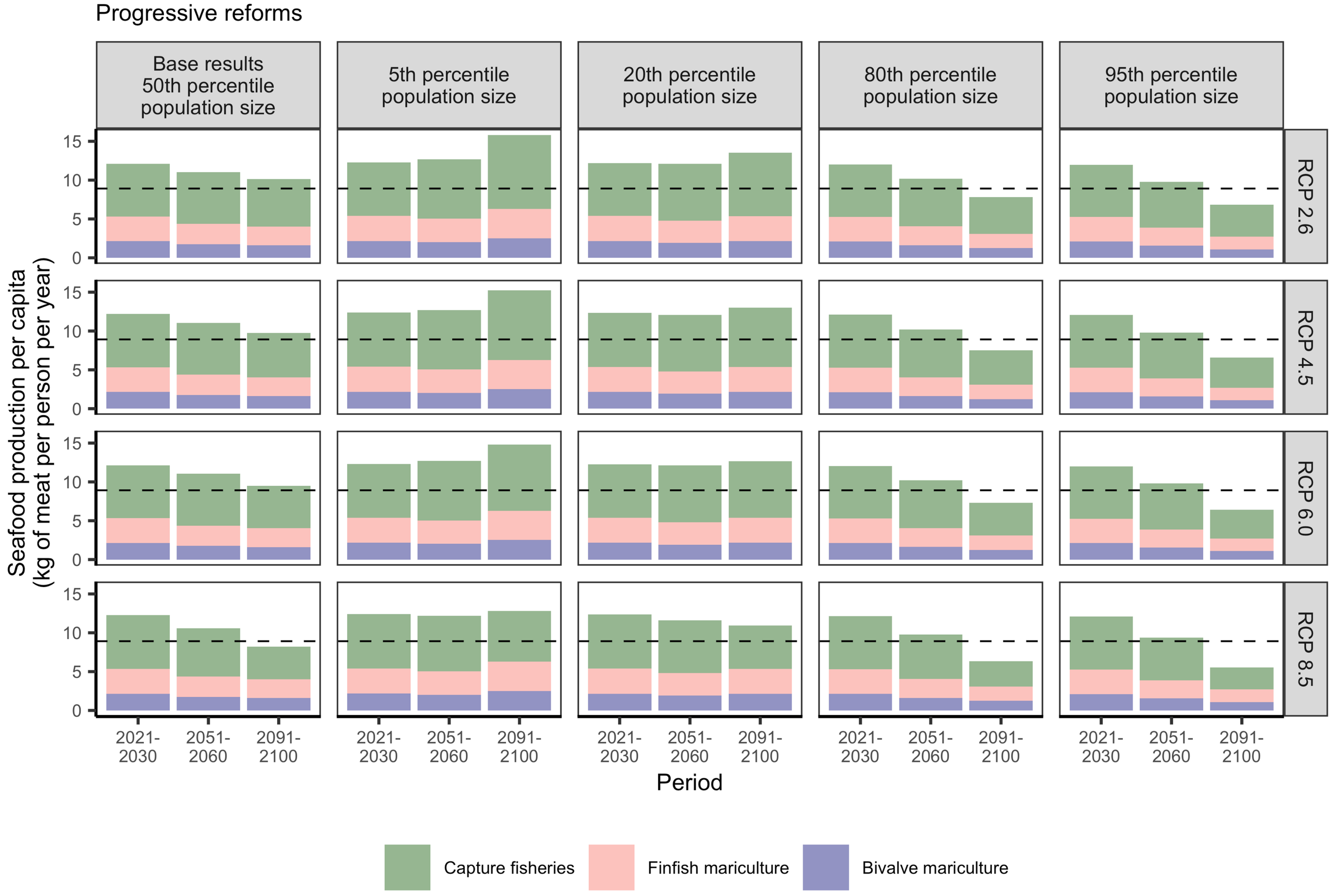
Extended Data Fig. 2 | Global seafood production *per capita* from marine fisheries and mariculture under climate change in the price and cost sensitivity analysis. In this analysis, mariculture seafood prices are 30% lower and mariculture operation costs are 30% higher than in our base scenario. Panels show (**a**) historical production per capita[48,49] and potential future production per capita under climate change and (**b**) business-as-usual (BAU) or (**c**) progressive reforms in fisheries and mariculture policies. In (**b**) and (**c**), dashed lines indicate current seafood production per capita. BAU fisheries management assumes that current harvest rates degrade as populations shift into new management areas whereas reformed fisheries management assumes that economically optimal harvest rates are maintained as populations shift into new management areas. BAU finfish mariculture policies assume moderate advances in "fish in, fish out" (FIFO) ratios (values projected for 2030; see Fig. 3) while reformed finfish mariculture policies assume substantial advances in FIFO ratios (values projected for 2050; see Fig. 3). Bivalve mariculture is the same in both policy scenarios.



Extended Data Fig. 3 | National seafood production trends and mariculture production footprints under different mariculture development scenarios in the price and cost sensitivity analysis. In this analysis, mariculture seafood prices are 30% lower and mariculture operation costs are 30% higher than in our base scenario. The top row shows the (**a**) percent of coastal countries (n = 164 countries) with increasing seafood production per capita from 2017 to 2091–2100 with progressive reforms in marine fisheries and mariculture under climate change and mariculture development scenarios. The bottom row shows (**b**) the percent of Exclusive Economic Zones (EEZs) (n = 164 countries) that would be developed for mariculture in 2091–2100 under each climate change and mariculture development scenario. Boxplots show the distribution of development percentages among countries and points show the percent of EEZs developed globally. High percentages occur in countries with very small EEZs (e.g., Belgium). 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. Note the log-scale y-axis. The current development scenario assumes that country's develop mariculture in proportion to today's production; the proportional development scenario assumes that country's develop mariculture in proportion to projected 2100 population size; the offset-based development scenario assumes that only countries losing seafood per capita from fisheries develop mariculture; and the optimum development scenario assumes that mariculture development is optimized to maintain seafood production per capita for the maximum number of countries.



Extended Data Fig. 4 | Seafood production per capita in the business-as-usual management scenario under climate change and alternative human population size trajectories. The main text results feature the 50th percentile population size projections shown in Supplementary Fig. 1.



Extended Data Fig. 5 | Seafood production per capita in the progressive reforms management scenario under climate change and alternative human population size trajectories. The main text results feature the 50th percentile population size projections shown in Supplementary Fig. 1.

nature portfolio

Corresponding author(s): Christopher M. Free

Last updated by author(s): January 10, 2022

Reporting Summary

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Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed	
☐	☒	The exact sample size (*n*) for each experimental group/condition, given as a discrete number and unit of measurement
☒	☐	A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☒	☐	The statistical test(s) used AND whether they are one- or two-sided *Only common tests should be described solely by name; describe more complex techniques in the Methods section.*
☒	☐	A description of all covariates tested
☒	☐	A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
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☒	☐	For null hypothesis testing, the test statistic (e.g. *F*, *t*, *r*) with confidence intervals, effect sizes, degrees of freedom and *P* value noted *Give P values as exact values whenever suitable.*
☒	☐	For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐	For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐	Estimates of effect sizes (e.g. Cohen's *d*, Pearson's *r*), indicating how they were calculated

Our web collection on statistics for biologists contains articles on many of the points above.

Software and code

Policy information about availability of computer code

Data collection	All data were curated using the R computing software (v. 4.0.3) and all data and code are available here: https://github.com/cfree14/aquacast. The following R packages were also used in data collection: wbstats (v. 1.0.4).
Data analysis	All data were analyzed using the R computing software (v. 4.0.3; R Core Team 2021) and all data and code are available here: https://github.com/cfree14/aquacast. Dozens of R packages were used in data analysis; especially important packages included: raster (3.4-5), sf (1.0-2), threadr (0.9.128), ncdf4 (v. 1.17), seacarb (v. 3.2.16), rfishbase (v.3.1.9), tidyverse (v. 1.3.1) , ggplot2 (v. 3.3.5).

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio guidelines for submitting code & software for further information.

Data

Policy information about availability of data

All manuscripts must include a data availability statement. This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our policy

The data that support this study are available here: https://github.com/cfree14/aquacast

The datasets used in the study are listed below along with their links/ascension codes:

WB (2020) human population growth data: https://data.worldbank.org/indicator/SP.POP.TOTL
UN-DESA (2017) human population growth data: https://population.un.org/wpp/
Free et al. (2020) fisheries projections data: https://doi.org/10.1371/journal.pone.0224347
FAO (2020) aquaculture production data: https://www.fao.org/fishery/en/statistics
AquaMaps (2020) environmental tolerance data: https://www.aquamaps.org/
FishLife (2018) species trait data: https://github.com/James-Thorson-NOAA/FishLife
FishBase (2020) species trait data: https://www.fishbase.de/
SeaLifeBase (2020) species trait data: https://www.sealifebase.ca/
GFDL-ESM2G (2012) earth system model climate data: https://www.gfdl.noaa.gov/earth-system-model/
Song et al. (2020) wave height data: https://www.nature.com/articles/s41597-020-0566-8

Field-specific reporting

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☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

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Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	We combine projections of human population growth, marine fisheries production, 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). Our forecasts of fisheries production are based on the climate-linked bioeconomic model results of Free et al. (2020) and present production outcomes under business-as-usual and climate-adaptive fisheries management scenarios. We forecast mariculture production potential using a climate-linked input-output model that accounts for the joint constraints of habitat suitability, competing ocean uses, economic feasibility, availability of feed for fed-mariculture (which depends on fisheries production), and consumer demand. We explore 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); 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). We evaluate the sensitivity of our results to scenarios in which prices are lower than today (as a result of increased production) and costs are higher than predicted by the model (due, potentially, to unaccounted for climate change impacts).
Research sample	We examined seafood production per capita in all 164 coastal countries with the required data. We examined all countries because this is a global analysis. Because we examined all countries, we did not need to sample. We considered the viability of all 144 mariculture species currently under production or considered for prediction. We examined all species because this is a comprehensive analysis. Because we examined all species, we did not need to sample.
Sampling strategy	We examined seafood production per capita in all 164 coastal countries with the required data. We examined all countries because this is a global analysis. Because we examined all countries, we did not need to sample. We considered the viability of all 144 mariculture species currently under production or considered for prediction. We examined all species because this is a comprehensive analysis. Because we examined all species, we did not need to sample.
Data collection	We wrote R code to download, format, and store the data. See all data and code here: https://github.com/cfree14/aquacast.
Timing and spatial scale	Our fisheries projections extend from 2012 to 2100 on annual time steps. Our mariculture projections describe three future periods: 2021-2030, 2051-2060, and 2091-2100. Our analysis is global and describe the Exclusive Economic Zones of 164 coastal countries.
Data exclusions	No data were excluded.
Reproducibility	All data and code are available on GitHub and the analysis is fully reproducible.
Randomization	Randomization is not relevant to our study. Our study is not an experiment or a survey. It uses a deterministic projection model. It does not use a stochastic projection model. Thus, randomization is not relevant or possible.
Blinding	Blinding is not relevant to our study. Our study is not an experiment or a survey. It is a computer simulation. Thus, blinding is not relevant or possible.

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Human research participants
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging