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Global change in marine aquaculture production potential under climate change

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Climate change is an immediate and future threat to food security globally. The consequences for fisheries and agriculture production potential are well studied, yet the possible outcomes for aquaculture (that is, aquatic farming)—one of the fastest growing food sectors on the planet—remain a major gap in scientific understanding. With over one-third of aquaculture produced in marine waters and this proportion increasing, it is critical to anticipate new opportunities and challenges in marine production under climate change. Here, we model and map the effect of warming ocean conditions (Representative Concentration Pathway scenario 8.5) on marine aquaculture production potential over the next century, based on thermal tolerance and growth data of 180 cultured finfish and bivalve species. We find heterogeneous patterns of gains and losses, but an overall greater probability of declines worldwide. Accounting for multiple drivers of species growth, including shifts in temperature, chlorophyll and ocean acidification, reveals potentially greater declines in bivalve aquaculture compared with finfish production. This study addresses a missing component in food security research and sustainable development planning by identifying regions that will face potentially greater climate change challenges and resilience with regards to marine aquaculture in the coming decades. Understanding the scale and magnitude of future increases and reductions in aquaculture potential is critical for designing effective and efficient use and protection of the oceans, and ultimately for feeding the planet sustainably.

Aquaculture (freshwater and marine) now produces more seafood than wild capture fisheries, with production expected to at least double by the mid-century[1,2] and growing international relevance to achieving the United Nations' Sustainable Development Goals[3]. The continuously expanding sector of marine aquaculture has tremendous potential to help feed the growing human population sustainably (for example, Sustainable Development Goals 2 and 14)[3,4], with most current cultivated seafood (excluding seaweeds) coming from fed finfish and unfed bivalves that filter phytoplankton (that is, primary producers) from the surrounding environment[2]. However, climate change may challenge future growth, stability and food security due to the suite of stressors and emerging interactions associated with shifts in temperature, primary production and ocean acidification[5], to name a few. Numerous studies have quantified the impacts of unsustainable harvest practices and climate change threatening wild fisheries around the world[6–8], yet we know comparatively little about the potential spatiotemporal impacts of climate change on the different types of aquaculture[9]. With aquatic farming's current and expanding role in the global food system, it is critical that we garner a greater understanding of when and where climate change may affect this 'blue growth' and future food security[3,9].

We use global ensemble model projections (historic to 2090) of sea surface temperature (SST) based on Representative Concentration Pathway scenario 8.5 (27 models; Supplementary Table 1), primary production (total chlorophyll; 14 models; Supplementary Table 1) and ocean acidification (aragonite saturation, Ω; CCSM3 model) to map the multispecies growth performance index (Φ') from 180 known marine culture species based on physiological tolerance and growth limits (K and L_∞, respectively)[4]. Modelling finfish ($n=120$ species) and bivalves ($n=60$ species) separately, we quantify the average suitable marine aquaculture area and Φ' within the exclusive economic zones (EEZs; that is, excluding high seas) over successive 20-year time intervals (relative to historic estimates; 1985–2005). We then use average Φ' to quantify the effect on production potential (ranges of percentage change seen across a given area) and the probability of countries experiencing declines (percentage of EEZs predicted to decline) in the future, based on the exponential relationship of the growth performance parameter and time-to-harvest of a typical finfish and bivalve farm (see ref. [4] and Methods for details).

Results

Globally, suitable waters expand for marine finfish aquaculture but contract for bivalves (Fig. 1). Suitable area is vast for finfish (historic estimate within all EEZs = 126.7 million km^2) and increases at an average rate of 0.8% (s.d. ± 0.2%) per 20-year interval, predominantly in polar and subpolar regions (Fig. 1a). A total of 13 countries see an expansion within their respective EEZs, including Russia (47% additional area), Norway (11%), the USA (via Alaska; 7%), Denmark (7%) and Canada (6%). Conversely, the suitable bivalve area historically is a fraction (9.8 million km^2) of what is available for finfish (due to the assumed levels of primary production required to support commercial growth; see Methods) and shrinks by 1 million km^2 by 2070–2090. Nearly every country (62 out of 69) experiences a loss of suitable area (0.01–100%) by the end of the century (Fig. 1b). Accounting for regions where Ω is less than 1.0 (the threshold when carbonate biominerals in shelled organisms may start dissolving)[10] reduces the suitable area almost twofold (1.7 million km^2). Furthermore, countries with currently suitable shellfish-growing areas that are impacted by the most extreme ocean acidification conditions ($n=8$) comprise current and significant bivalve producers, including China, Canada, the USA and Russia (Supplementary Fig. 2).

Within the suitable areas, the average production potential for finfish aquaculture appears comparatively more favourable

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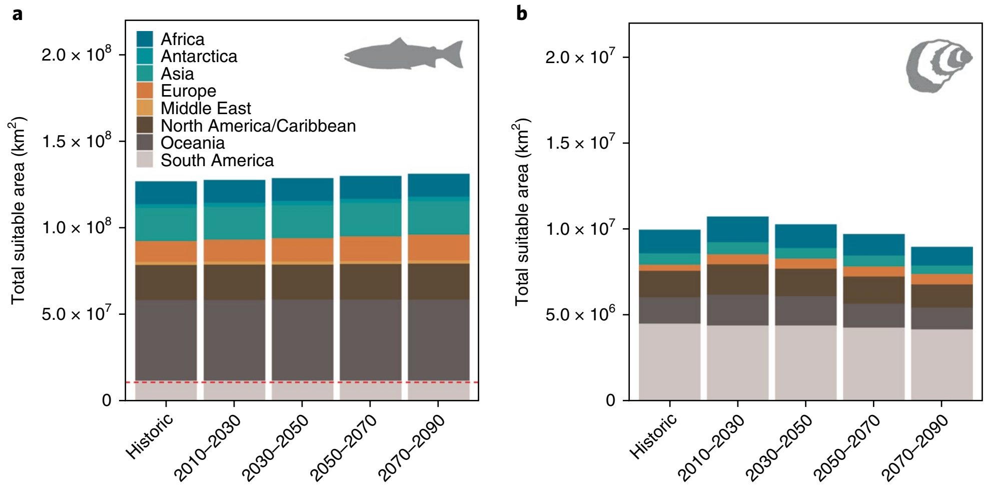

Fig. 1 | Total average suitable area for finfish and bivalves by time and region. a,**b**, Suitable areas are shown for finfish (**a**) and bivalves (**b**) for different time steps (historic (1985–2005) to 2070–2090) and regions. For reference, the red dashed line in **a** depicts the maximum bivalve area (t_1 = 2010–2030). See Supplementary Fig. 1 for s.d. values (globally too small to depict here).

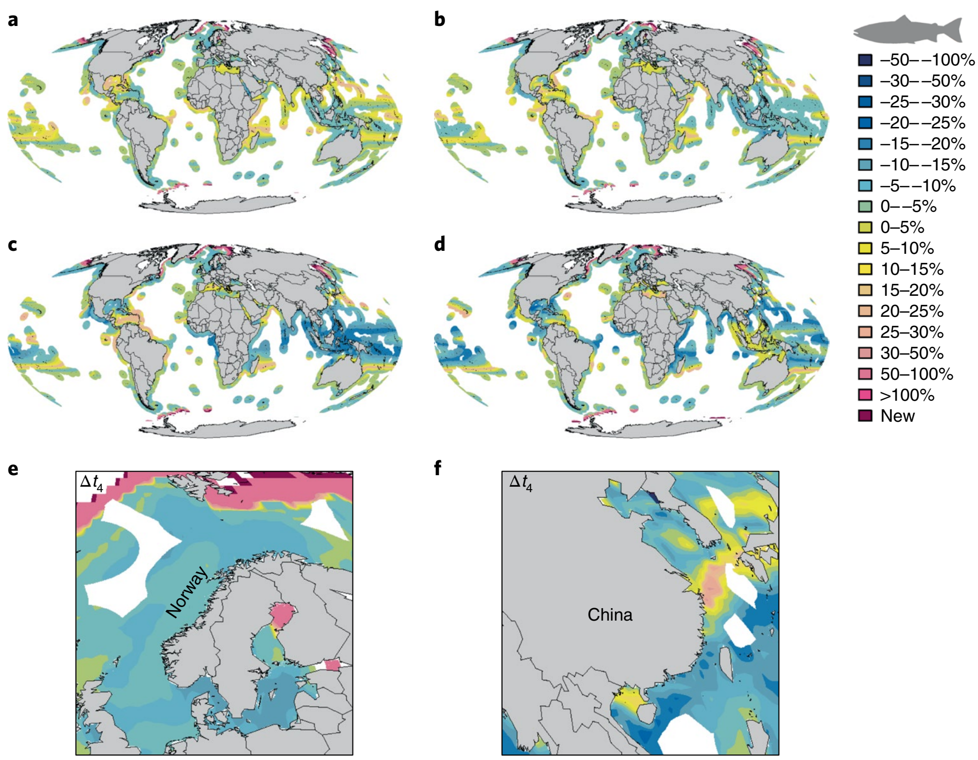

Fig. 2 | Average percentage change in finfish aquaculture production potential over time. a–**d**, Changes are shown for 2010–2030 relative to historic (1985–2005; Δt_1; **a**), 2030–2050 relative to 2010–2030 (Δt_2; **b**), 2050–2070 relative to 2030–2050 (Δt_3; **c**) and 2070–2090 relative to 2050–2070 (Δt_4; **d**). **e**,**f**, Percentage changes for subpolar waters around Norway (**e**) and surrounding China (**f**) for Δt_4. Maroon areas indicate new suitable waters. White space represents the high seas and/or unsuitable temperatures (Arctic conditions). See Supplementary Fig. 3 for s.d. values.

in earlier time periods (smaller and fewer declines in most EEZs; Fig. 2a), but declines become more extensive over time, with the most pronounced differences occurring in tropical and subpolar regions (Fig. 2b–d). By the third average time interval (2050–2070; Fig. 2c), waters around the Indo-Pacific, Mexico and Canada are predicted to experience some of the largest reductions in production potential (10–20%; cumulative (Δt_{1+2+3}) range = −15–30%). By the end of the century, reductions continue in most of these regions and, to a lesser extent, around the major finfish producers Norway and China (Fig. 2e,f and Supplementary Fig. 2a). However, some tropical and subtropical areas are anticipated to see continued and large potential gains in production potential (cumulative ($\Delta t_{1+2+3+4}$) range = +30–40%; Supplementary Fig. 2a), including within the Caribbean and Mediterranean seas (Fig. 2a–d).

Similar to finfish patterns, production potential declines in most of the suitable bivalve area over time, with some areas even disappearing completely due to changing temperatures and contraction of chlorophyll (and possibly due to Ω dropping below 1.0)

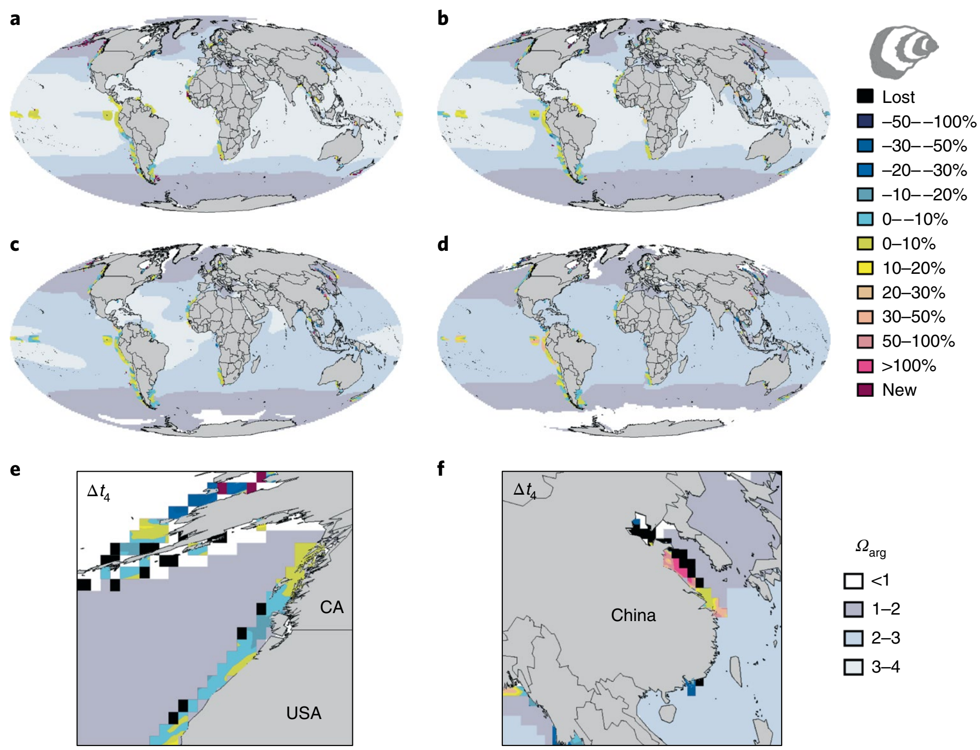

Fig. 3 | Average percentage change in bivalve aquaculture production potential over time. a–d, Changes are shown for 2010–2030 relative to historic (1985–2005; Δt_1; **a**), 2030–2050 relative to 2010–2030 (Δt_2; **b**), 2050–2070 relative to 2030–2050 (Δt_3; **c**) and 2070–2090 relative to 2050–2070 (Δt_4; **d**). **e**,**f**, Percentage changes for the west coast of North America (**e**) and around China (**f**) for Δt_4. Maroon areas indicate new suitable waters. Black regions (only displayed in **e** and **f**) represent lost suitable area from all previous time steps. Average Ω levels greater than 1.0 are shown in the background as purple gradients, and levels less than 1.0 are depicted in white. See Supplementary Fig. 4 for s.d. values.

(Fig. 3a–d). Around the mid-century mark and thereafter, most countries have waters that decline in production potential (5–20% declines), with some regions experiencing modest increases, such as the west coast of North America (Fig. 3e). Several major producers of bivalves, including China, Thailand and Canada, may see more dramatic declines in production potential (50–100%) in parts of their EEZs (Fig. 3b–d; cumulative ($\Delta t_{1+2+3+4}$) range = −20–100%; Supplementary Fig. 2b). Notably, while some initially suitable waters around China decline and disappear (Yellow Sea), adjacent zones show the opposite pattern, with some of the largest rebounds and net gains in potential production (Fig. 3f; cumulative $\Delta t_{1+2+3+4} > 100\%$; Supplementary Fig. 2b). In addition, the expanding average declines of Ω towards the equator will significantly challenge subpolar and temperate nations already expected to experience bivalve declines from changing temperature and shifting chlorophyll, and may further limit production (Fig. 3a–d).

Given the heterogeneous changes in aquaculture production potential, we calculated the probability (percentage of suitable area) of a given region experiencing declines. Globally, the probability of production potential decreasing within suitable areas of all EEZs reaches approximately 50% by the mid-century for both finfish and bivalves (Fig. 4a,b), with bivalve areas tending towards larger reductions than finfish (probability of declines >10%, Supplementary Fig. 5). In the first average time step (2010–2030) relative to historic conditions, the probability of production potential declines is only 33 and 28% for finfish and bivalves, respectively, such that most areas are currently experiencing equivalent or larger growth potential. However, declines become more probable by 2030–2050 (46 and 41%) and appear to level off by 2050–2070 (50 and 45%; Fig. 4a,b). Patterns are spatially variable, so any particular country will experience a higher or lower probability within their respective EEZ (see Supplementary Data 1 for full list). For example, top aquaculture-producing countries in Asia are predicted to experience much more persistent and ubiquitous declines for finfish and bivalves (probability of declines >50%) sooner rather than later (Fig. 4c,d and Supplementary Fig. 2). In contrast, most countries in South America have decline probabilities of their suitable areas below 50% across time and taxonomic group (Fig. 4c,d).

Discussion

Projected declines in aquaculture production potential could affect global economies and food security, especially if current spatially skewed production patterns persist in the future (Supplementary Fig. 2a,b). Countries in Asia currently produce about 90% of all marine cultured biomass[2] and may face depressed growth for finfish and bivalves. Selective breeding may compensate for some reductions in growth performance[11], but species on the edge of their tolerance limits[12], possible trade-offs between growth and tolerance performance[13], the presence of multiple stressors[12] and barriers to technology transfer[14] could impede such practices. Globally, countries with improved or less impacted regions could add stability and accessibility through trade. At the country level, heterogeneity of the waters in a country's EEZ could mitigate the change in production potential for some areas, depending on farm location—especially for countries with vast marine availability (for example, the USA). The percentage of productive waters needed to meet seafood demands is minute[4], so even if production potential declines in most areas, optimal species and/or placement of farms could result in an overall increase in biomass in the future. Yet, the negative impact of changes in aquaculture production potential could be amplified in regions that disproportionally depend on seafood[15,16], rely on domestic aquaculture production (economic or subsistence)[17] and

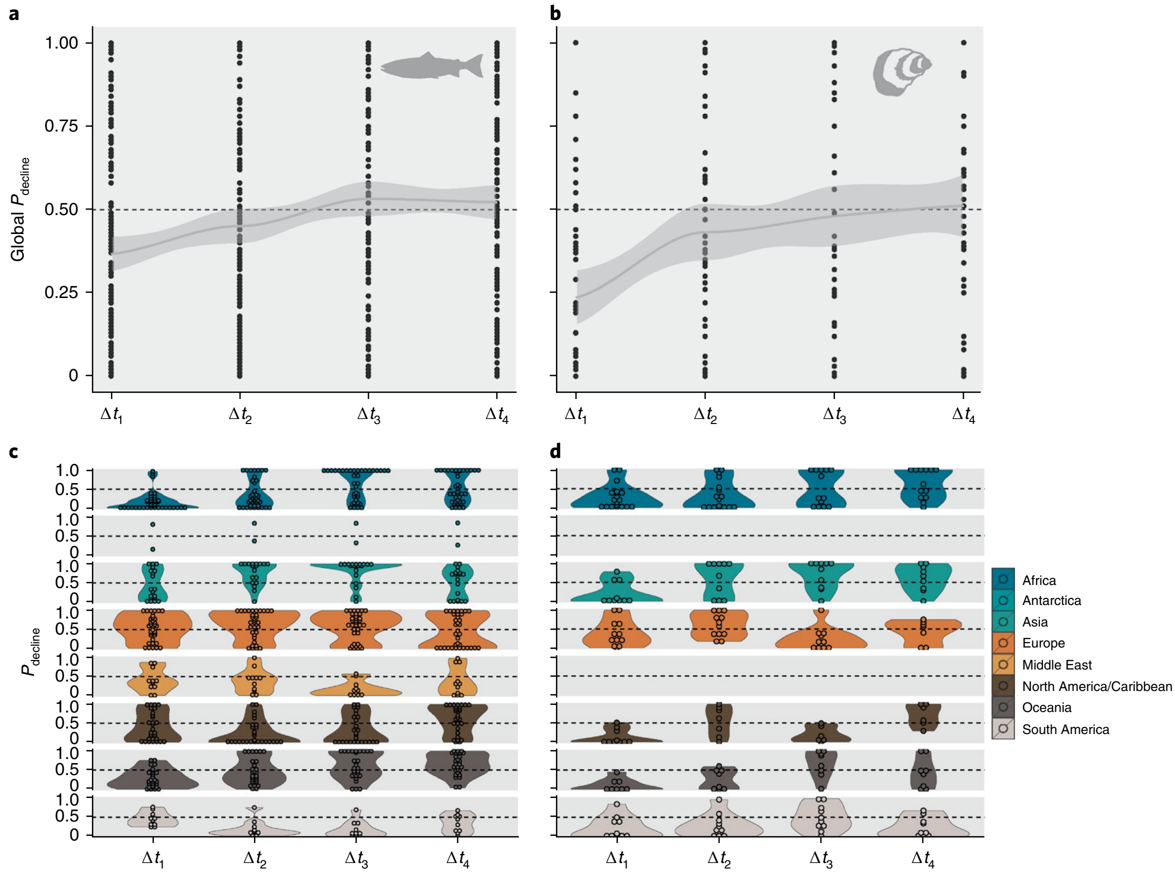

Fig. 4 | Probability of the aquaculture production potential declining over time. a–d, Decline for a given country (EEZ) globally (**a** and **b**) and regionally (**c** and **d**) for finfish (**a** and **c**) and bivalves (**b** and **d**). The global and regional representations over each time step span from 0 to 1.0, with 0.5 indicated by dashed lines. A loess smoother (±95% confidence interval) was fitted for average reference of the nonlinear trajectory for the global plots in **a** and **b**. Each dot represents a country or territory. See Supplementary Fig. 5 for trends of declines >10%.

are likely to see continued declines in wild fisheries due to overfishing and climate change, such as those in the Indo-Pacific region[9,18]. Ultimately, the identification of which areas are more or less resilient to climate change is critical for future policy, development and adaptive management, especially under social and economic constraints not captured in this study.

Increasing attention is being given to bivalve aquaculture because of its lower cost and possible impact on the surrounding environment compared with finfish (for example, bivalves are filter feeders and produce less pollution)[19]; however, similar to wild species[16,20], cultured bivalves may be less resilient to cumulative stressors[13]. Bivalves are currently the most farmed taxa in marine waters, particularly in Asia and North America[2], but require favourable conditions of enough food and shell-forming minerals pre- (if water is not buffered) and post-seeding to survive and grow in the marine environment. Our model shows comparatively larger declines and loss of suitable waters due to the triple threat of changes in temperature, primary production and ocean acidification, which emphasize the importance of adaptive planning (for example, siting and species) for current producers and nations investing in future aquaculture development. Nearshore biophysical dynamics—where the majority of marine production currently occurs—can influence local-level carbonate conditions[21], and patterns of future phytoplankton production are less precise than other modelled biophysical processes (hence the use of ensemble outputs)[22]. However, the general patterns and comparison with finfish reported here provide a critical global perspective on the potential limits and success of different types of aquatic species cultivated in the marine environment under a suite of future anthropogenic climate-driven pressures.

Finfish appear more resilient than bivalves in the changing climate, but other factors could limit growth and production for both taxonomic groups in the future. Although they are difficult to predict, a higher frequency, extent and magnitude of harmful algal blooms[23], disease outbreaks[24–26] and hypoxic zones[27] have all been linked to increases in temperature at different spatiotemporal scales. Similarly, shifts in precipitation and sea level rise, which are not captured in this study, will continue to stress cultured (and wild) marine species in more nearshore systems[28–30]. Other human uses of the ocean (for example, shipping and marine protected areas) will also probably constrain future development[4], so baseline knowledge of potentially more or less suitable areas under climate change will be critical for planned management and sustainable development.

Aquaculture is the new frontier of seafood production, and climate change will test the future stability of the sector and contribution to food security. Regions without agency or capital to adapt may be particularly vulnerable to aquaculture losses—especially countries dependent on seafood. Challenges and opportunities will also emerge in the 'marine klondike' as conditions warm in polar extents[31], especially with the nascent but growing sector of offshore aquaculture[4,11,32]. While an unlikely and comparatively smaller threat to the Arctic than shipping or fishing, marine aquaculture may add an additional pressure and warrant proactive planning given the proximity of suitable expansion to some of the leaders in aquaculture research and development (for example, Norway).

Ultimately, understanding how these patterns compare and link to other food systems and aquaculture practices (for example, freshwater) will be essential to account for the full scope of possible climate change impacts on future food and sustainability goals around the world[5,9].

Methods

Overview. Using the marine aquaculture species data (120 finfish and 60 bivalves) and methods of Gentry et al.[4] (Supplementary Table 2), we spatially model the future production potential for finfish and bivalve aquaculture under climate change. Based on physiology, allometry and growth theory, the approach is a comparative, non-species-specific method used to model the relative change in potential aquaculture production over time. Primarily dictated by the thermal limits of species (bounded by ensemble-predicated SST ranges), we further assess the future conditions and potential consequences (change in suitable area and percentage production potential) by constraining waters by countries' EEZs, total chlorophyll (ensemble) and ocean acidification (based on aragonite saturation). Below, we describe: (1) modelling of the aquaculture production potential; and (2) the predicted ecological constraint layers that bound the suitable production area over space and time.

Production potential. With over 200 species cultured in the marine environment[2] and a dearth of species-specific growth performance data, the use of Φ' leverages data on species' thermal limits and Von Bertalanffy growth parameters that are more readily available in the scientific literature[4,13]. Thus, use of the growth performance indicator reflects the broader spatiotemporal trends of climate change on aquaculture across the oceans. The approach assesses the composite species potential; thus, choosing specific species that are more resilient to predicted changes in any given location may help mitigate potential climate change impacts. All methods of data collection and application of the multispecies Φ' are described in detail in Gentry et al.[4], and the corresponding equations and parameters are provided in the Supplementary Information (Supplementary Table 2).

Briefly, we determine which aquaculture species (finfish and bivalves evaluated separately) can occur in a given grid cell (1 × 1°) based on the respective species' thermal tolerance ranges (maximum and minimum limits) and the spatially projected mean SST (described in detail below) annual ranges (maximum and minimum) of that cell. We then average across the species to calculate multispecies Φ' values for each cell. The yearly Φ' values are then averaged over 20-year time steps and compared (Supplementary Figs. 6 and 7). The time steps of this study include historic (1985–2005), 2010–2030 (t_1), 2030–2050 (t_2), 2050–2070 (t_3) and 2070–2090 (t_4). Based on the means, production per unit area is then calculated based on conversion of the 20-year Φ' values to time-to-harvest for typical taxa (finfish: 35 cm; bivalves: 4 cm) and farm size (Supplementary Table 1).

The suitable areas are further constrained—beyond just thermal limits—by the EEZs for finfish and bivalves, and chlorophyll and ocean acidification for bivalves (described in detail below). Unlike wild fisheries, we bound aquaculture potential by the EEZs assuming it is unlikely that any particular company or individual would try to establish a farm outside a country's jurisdiction due to social uncertainty and cost. Based on this same logic, we omit disputed waters, resulting in an assessment of 171 countries or territories. All layers are projected to mollweide to calculate area (km^2).

The spatiotemporal production values are assessed in three ways. First, the change in total area (km^2) and percentage production potential at each respective time step are calculated and mapped. Second, we calculate and map the cumulative change (or net change) in productive potential by summing across the four percentage-change intervals. The individual percentage changes at each time step provide the relative 20-year shifts in productivity (Figs. 2 and 3), while the cumulative calculations show the regions that result in a net positive or negative region by the end of the century (Supplementary Fig. 2). Lastly, the total area (km^2) of negative versus positive changes in productivity within the EEZs is calculated, providing the probability of any suitable area globally or given country experiencing a decline (or increase) in production potential over time (Fig. 4 and Supplementary Fig. 5). Again, all analyses are performed separately for finfish and bivalves.

In addition to the Φ' means and associated change in production potential, s.d. values are calculated for each time interval for an estimate of regional, temporal certainty (Supplementary Figs. 3, 4, 8 and 9). The most variable regions are those on the polar edge of suitability for finfish (Supplementary Figs. 3 and 8) and around China and Russia for bivalves (Supplementary Figs. 4 and 9). We also provide reference to the mean (Supplementary Figs. 10 and 11) and s.d. (Supplementary Figs. 12 and 13) of the number of species suitable to calculate the growth performance index of a particular ocean cell over time. All analyses are performed in R version 3.4.1 (ref. [33]).

Ecological constraint layers. *SST projections.* Ensemble projections—the new standard in fisheries and climate modelling[34,35]—of global SST are used as the foundation for mapping the waters that are thermally suitable for finfish and bivalve aquaculture in the future (Supplementary Fig. 14). The intent of this study was to capture the climate change 'signal' for marine aquaculture, which becomes most apparent with an ensemble approach, particularly at a global scale[34]. To separate signal from noise, we use the ensemble outputs of 27 SST models (1 × 1°; Supplementary Table 1) from the fifth phase of the Coupled Model Intercomparison Project (CMIP5). We specifically use Representative Concentration Pathway scenario 8.5 (high emissions)—the most extreme, but ever more likely, conditions of the future[36]. To determine the thermal suitability, we extract and use the yearly minimum and maximum values from the monthly predictions (historic: 1985–2005; future: 2010–2090). Model outputs were obtained through the National Oceanic and Atmospheric Administration (NOAA) Climate Change Web Portal (https://www.esrl.noaa.gov/psd/ipcc/ocn/ccwp.html).

It is important to note that while the ensemble approach captures the broader influence of climate change, it does not necessarily represent circulation patterns and biophysical feedbacks at smaller scales. Yet, downscaling and/or the use of a single model (instead of ensemble) contains inherent model biases and may obfuscate the climate change signal[34], the main objective of this global study. Another recently published study used a single, higher-resolution model (GFDL CM 2.6) to assess three cultured finfish species (Atlantic salmon *Salmo salar*, gilthead seabream *Sparus aurata* and cobia *Rachycentron canadum*), based on optimal growth relative to average monthly SST to 2050[11]. The modelling approach and assumptions, number of species, and time span differ considerably between the two studies, making it difficult to compare the results as currently presented. Nonetheless, downscaled comparisons could be performed in the future, similar to research being conducted in other oceanographic fields (for example, ref. [37]). In addition, international efforts are addressing climate change projections for fisheries and marine ecosystem model ensembles[35].

Chlorophyll projections. Thermal limits (maximum and minimum) are the primary factor for determining suitability for finfish and bivalves, but bivalves—a filter-feeding aquaculture group—require sufficient levels of phytoplankton in the surrounding environment to successfully survive and grow[38,39]. Other studies have found chlorophyll-a to be a good proxy for food availability for bivalves[37,38]. Our modelling approach assumes no feed limitation and is thus most appropriate and applicable in locations with consistent concentrations of chlorophyll, as described in previous studies, on which we modelled our approach[4].

Similar to SST, we use average ensemble model outputs (14 models; Supplementary Table 1) for total chlorophyll concentration (1 × 1°; kg m^{-3}; Supplementary Figs. 15 and 16). We use ensemble outputs to accommodate for the higher level of uncertainty—compared with other oceanographic processes—in predicting future phytoplankton production levels[22,40]. From these outputs, we need to capture high and stable enough primary production levels to support commercial bivalve growth[4]. We cannot use the exact threshold described in Gentry et al.[4] because the model outputs are total chlorophyll (not just chlorophyll-a) and ensemble methods dampen intra-annual variability. Instead, to account for some level of the variability, we calculate the mean and s.d. of chlorophyll over the same time span and intervals as SST. We then subtract the respective chlorophyll s.d. values from the means and compare the spatial patterns of the historic results with those reported in Gentry et al.[4] from the Moderate Resolution Imaging Spectroradiometer (MODIS) satellites (mean 2003–2014). Through a stepwise progression of 50 kg m^{-3} increments, we find a limit of 400 kg m^{-3} (historic mean – s.d. concentration > 400 kg m^{-3}) most closely resembles the empirical spatial productivity requirements, which we use to further constrain suitable bivalve aquaculture area over time and space (Supplementary Fig. 15). Similar to Gentry et al.[4], we capture the least variable and most primary productive regions of the oceans, but the chlorophyll areas are conservative and do not account for all potentially productive waters. The spatial extents are not identical because we use predictive models, ensemble outputs and total chlorophyll. Nonetheless, our approach still provides a larger, comparative assessment of when and where changes may affect marine aquaculture in the future (Supplementary Fig. 16). Ensemble model outputs were also obtained from the NOAA Climate Change Web Portal (https://www.esrl.noaa.gov/psd/ipcc/ocn/ccwp.html).

Ocean acidification projections. Ocean acidification is a major threat to wild and farmed species, particularly shell-forming organisms[10,28,41]. How species respond to the changing acidity of marine environments can depend on species adaptive capacity[42], rates of change[16,43] and complex biophysical feedbacks[21] that are difficult to capture at the global scale. However, because ocean acidification is a current and growing threat to predominantly shellfish aquaculture, we use predicted future levels of Ω—originally modelled in Feely et al.[10] (Supplementary Table 1; 1 × 1°)—to capture a base-level threat to the suitable bivalve areas initially bounded by SST and chlorophyll limits (described above). Using $\Omega < 1.0$ as a global threshold (saturation level at which the carbonate biominerals of shells and skeletons may begin to dissolve)[10,44], we calculate the relative area and countries most at risk from such acidified conditions relative to the other external factors. This also provides qualitative understanding of areas that may be impacted by other interacting ecological effects of ocean acidification, such as greater energetic costs of additional acid–base regulation that could decrease the growth and possible condition of farmed organisms[45,46]. Model outputs were provided by the Woods Hole Oceanographic Institution.

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

Data availability

Computer code and data products reported in this paper are publicly accessible from the Knowledge Network for Biocomplexity data repository: https://doi.org/10.5063/F1SX6BDP.

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Author contributions

H.E.F., R.R.G. and B.S.H. conceived the initial study. H.E.F. and R.R.G. developed the research and methodology, with critical input and insight from B.S.H. H.E.F. and R.R.G. collected and processed the data. H.E.F. conducted the analyses. All authors interpreted the results and implications. H.E.F. produced the figures. H.E.F. drafted the manuscript with significant input and revisions from all authors.

Competing interests

The authors declare no competing interests.

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Policy information about availability of computer code

Data collection	Species data were downloaded from Gentry et al. (2017) from the KNB: Knowledge Network for Biocomplexity data repository, model outputs for sea surface temperature and chlorophyll were obtained through the National Oceanic and Atmospheric Administration (NOAA) Climate Change Web Portal, and model outputs for ocean acidification were provided by Woods Hole Oceanographic Institution.
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Study description	We model and map the effect of warming oceans conditions (RCP 8.5) on marine aquaculture production potential over the next century. We use global ensemble model projections (historic – 2090) of sea surface temperature (RCP 8.5, 27 models), primary production (total chlorophyll, 14 models), and ocean acidification (OA, aragonite saturation Ω, CCSM3 model) to map the multispecies Growth Performance Index (Φ').
Research sample	Production potential of marine culture species is based on thermal tolerance and growth data of 180 cultured finfish and bivalve species. Model projections span 1985-2090.
Sampling strategy	NA
Data collection	Species data were from Gentry et al. (2017) from the KNB: Knowledge Network for Biocomplexity data repository, model outputs for sea surface temperature and chlorophyll were obtained through the National Oceanic and Atmospheric Administration (NOAA) Climate Change Web Portal, and model outputs for ocean acidification were provided by Woods Hole Oceanographic Institution.
Timing and spatial scale	Model outputs span 1985-2090, globally.
Data exclusions	NA
Reproducibility	Computer code and data products reported in this are publicly accessible on the KNB: Knowledge Network for Biocomplexity data repository.
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

Reporting for specific materials, systems and methods

Materials & experimental systems

n/a	Involved in the study	
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☒	☐	Antibodies
☒	☐	Eukaryotic cell lines
☒	☐	Palaeontology
☒	☐	Animals and other organisms
☒	☐	Human research participants

Methods

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