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Mapping the global potential for marine aquaculture

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Marine aquaculture presents an opportunity for increasing seafood production in the face of growing demand for marine protein and limited scope for expanding wild fishery harvests. However, the global capacity for increased aquaculture production from the ocean and the relative productivity potential across countries are unknown. Here, we map the biological production potential for marine aquaculture across the globe using an innovative approach that draws from physiology, allometry and growth theory. Even after applying substantial constraints based on existing ocean uses and limitations, we find vast areas in nearly every coastal country that are suitable for aquaculture. The development potential far exceeds the space required to meet foreseeable seafood demand; indeed, the current total landings of all wild-capture fisheries could be produced using less than 0.015% of the global ocean area. This analysis demonstrates that suitable space is unlikely to limit marine aquaculture development and highlights the role that other factors, such as economics and governance, play in shaping growth trajectories. We suggest that the vast amount of space suitable for marine aquaculture presents an opportunity for countries to develop aquaculture in a way that aligns with their economic, environmental and social objectives.

As the human population looks set to reach 10 billion people by 2050[1], our food systems will be under intense pressure to produce animal protein for an increasing population[2]. Faced with plateauing wild fishery catches[3] and high impacts from land-based agriculture[4,5], momentum is building to look towards marine aquaculture to meet the growing protein demand[6,7]. The relative sustainability of marine aquaculture compared with land-based meat production[8] and the human health benefits of diets rich in fish[9] make it even more pressing that we consider aquaculture's potential. Oceans represent an immense opportunity for food production, yet the open ocean environment is largely untapped as a farming resource.

The majority of existing aquaculture takes place on land, in freshwater and in nearshore marine waters[10]. However, problems, such as high resource use, pollution and habitat destruction have created a generally negative reputation for aquaculture in several countries[11,12] and pose challenges for continued expansion. Open-ocean aquaculture appears to have several advantages over the more traditional culturing methods, including fewer spatial conflicts and a higher nutrient assimilation capacity[13,14], highlighting the opportunities for sustainable marine development. However, large-scale open-ocean farms are not yet common, making adaptive management and careful research an essential element of sustainable marine aquaculture expansion.

Despite the perception that marine aquaculture has high growth potential[15,16], little is known about the extent, location and productivity of potential growing areas across the globe. Most of the research on marine aquaculture potential has focused on specific species[17] and/or specific regions[18,19], and there remains an important need to assess the more general growing potential across locations. To rectify this shortfall, we drew on physiology and growth theory coupled with environmental data to quantify and map the global potential for fish and bivalve aquaculture. These categories represent two major types of culture: fed aquaculture, where food is provided from an external source, and unfed aquaculture, where nutrition comes from the environment. We focused on quantifying a realistic biological baseline given the diversity of existing ocean uses, thus providing novel insight into the potential global aquaculture production and the role it might play in addressing future food security. Ultimately, the economic and social constraints of aquaculture may limit production, and their inclusion in future research will help further refine realistic production potential.

To characterize aquaculture's potential, we used a three-step approach (see Methods). First, we analysed the relative productivity for each 0.042 degree^2 patch of global ocean for both fish and bivalve aquaculture. To do this, we constrained the production potential for each of 180 marine aquaculture species (120 fish and 60 bivalves) to areas within their respective upper and lower thermal thresholds using 30 years of sea surface temperature data (Supplementary Fig. 1). We then calculated the average (multi-species) growth performance index (GPI) for each patch for all suitable fish and bivalve species, resulting in a spatially explicit assessment of the general growing potential for each aquaculture type (Supplementary Fig. 2). GPI is derived from the von Bertalanffy growth equation and uses species-specific parameters (growth rate and maximum length[20]) to create a single metric to describe the growth potential of a species[21]. GPI has been used frequently to assess growth suitability for culture and is particularly useful for fed species or those not subject to food limitations[22–24]. Locations with a high GPI are expected to have better growth conditions for a spectrum of aquaculture species and, thus,

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are well suited to development. Using a multi-species GPI average to assess growth potential provides a more general growth suitability metric than is possible when making detailed assessments for a single species. This approach is especially useful given the fast rate at which new species are being developed for aquaculture and the shift in focal species between nearshore and offshore cultures[14,25,26]. Moreover, using GPI averages across species provides a conservative assessment, since we are considering an average rather than the maximum growth potential.

Second, once the production potential was determined, we removed unsuitable areas with certain common environmental or human-use constraints. We excluded areas with unsuitable growing conditions due to low dissolved oxygen (fish only) and low phytoplanktonic food availability (bivalves only). We also eliminated areas at > 200 m depth because they are generally too deep (and thus expensive) to anchor farms, and areas already allocated to other uses, including marine protected areas, oil rigs and high-density shipping areas (Supplementary Fig. 5 and Supplementary Table 1). We acknowledge that advancing technology may alleviate some of these constraints through innovative farm designs that allow for deeper mooring and submerged farming structures. However, these constraints reflect the current common industry practice and provide a more conservative and economically realistic projection of potential. For the third and final step, we estimated the idealized potential production per unit area by converting the average (multi-species) GPI into biomass production, assuming a low stocking density is used and the farm design is uniform across space.

Results and discussion

We found that over 11,400,000 km^2 are potentially suitable for fish and over 1,500,000 km^2 could be developed for bivalves. Both fish and bivalve aquaculture showed expansive potential across the globe, including both tropical and temperate countries (Figs. 1 and 2 and Supplementary Table 3). However, as would be predicted by metabolic theory[27], many of the areas with the highest GPI were located in warm, tropical regions. The total potential production is considerable: if all areas designated as suitable in this analysis were developed (assuming no further economic, environmental or social constraints), we estimate that approximately 15 billion tonnes of finfish could be grown every year—over 100 times the current global seafood consumption.

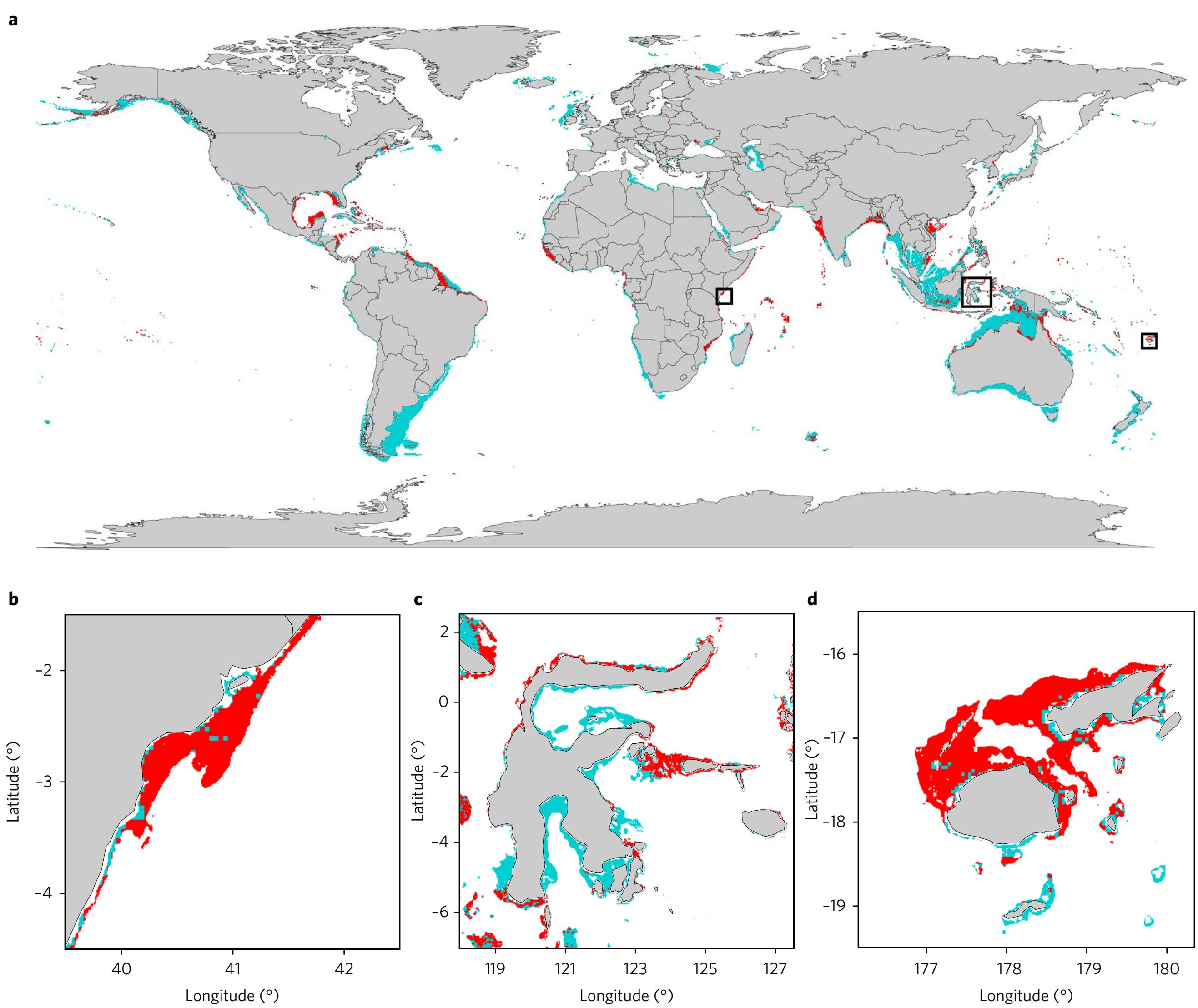

Fig. 1 | Global hotspots for finfish aquaculture. a, The blue and red areas depict the locations that have potentially suitable growing conditions for marine aquaculture and were not excluded due to the conflicting uses included in the analysis. Red signifies areas with the highest (top 20%) potential productivity. **b–d**, Zoomed-in areas for the southern coast of Kenya (**b**), central Indonesia (**c**) and Fiji (**d**). These locations are indicated by black rectangles in **a**.

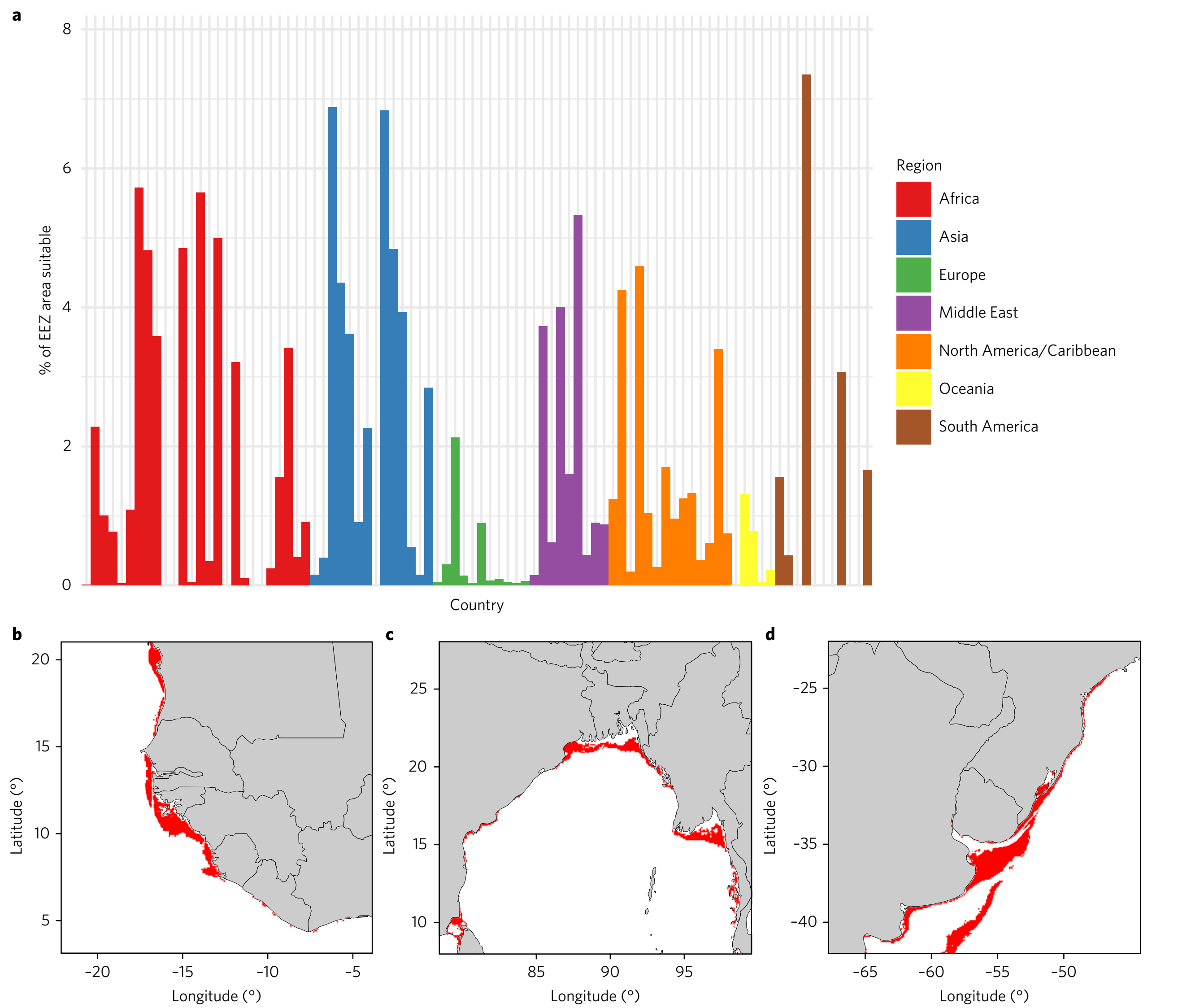

Fig. 2 | Potential growing area for bivalves by country. a, Percentage of each country's exclusive economic zone (EEZ) that has potentially suitable growing conditions for bivalves and no known conflicting uses. Each bar represents a single country grouped by region. **b–d** Potential bivalve growing areas (red) centred on Guinea (**b**), Bangladesh (**c**) and Uruguay (**d**). These are the countries with the highest percentage suitable areas for bivalves in Africa, Asia and South America, respectively. More detail is provided in Supplementary Fig. 7.

Although this analysis clearly shows vast aquaculture potential, there are important additional environmental and socioeconomic factors that would rule out seemingly suitable space. For example, a more refined assessment may exclude environmentally sensitive or high biodiversity areas, such as coral reefs. Other areas might be avoided due to economic considerations, such as the distance to ports, access to markets, shoreside infrastructure, and intellectual or business capital. The social interactions with wild fisheries, jobs, prices and cultural heritage should also be taken into consideration. Other uses of these areas, such as by the military or for energy production, may also limit the available space. The actual zones suitable for aquaculture development will certainly be smaller than the identified areas. However, the scale of potential space suggests high flexibility in siting farms according to more nuanced constraints.

Nearly every coastal country has high marine aquaculture potential and could meet its own domestic seafood demand, assuming no other limiting factors, typically using only a minute fraction of its ocean territory (Fig. 3). While the global potential is vast, certain countries show particular promise. Indonesia, for example, has among the highest annual production potential for both fish and bivalves. Developing only 1% of Indonesia's suitable ocean area could produce more than 24 million tonnes of fish per year or over 3.9×10^{11} individual 4 cm bivalves. If consumed entirely within Indonesia, this volume of additional fish production would increase seafood consumption per capita sixfold. In fact, there is already considerable activity working to expand Indonesian aquaculture[28].

The large production potential per unit area for marine aquaculture enables the possibility of producing significant amounts of seafood using limited ocean space. For example, we calculate that if only the most productive areas of the ocean were developed for fish aquaculture, the amount of seafood that is currently captured by all wild fisheries[3] could be grown using less than 0.015% of the ocean's surface area—a surface area less than Lake Michigan. This calculation provides an important assessment of the spatial scope of ocean seascapes that may be affected by expanding marine production, but does not account for the space (likely on land) that would be needed for feed production or processing. While aquaculture could successfully take place in oceans around the world, the strategic placement

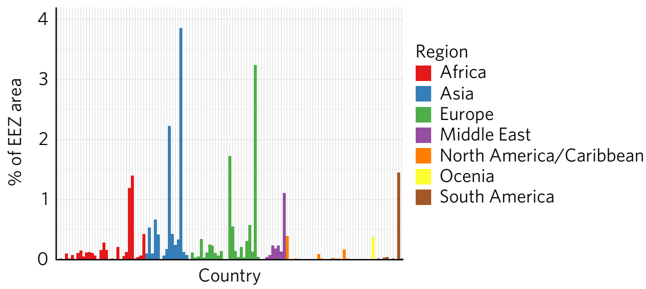

Fig. 3 | Percent of each country's EEZ required for finfish aquaculture to supply its current seafood consumption. Each bar represents a single country grouped by region. The vast majority of countries would need to farm much less than 1% of their EEZ to produce all of the seafood they are currently consuming. More detail is provided in Supplementary Fig. 8.

of farms in areas with high potential productivity would allow for maximum production with a minimized ocean footprint. Space minimization in aquaculture production is not currently a key concern in most development, but it may become increasingly relevant as areas of the ocean become subject to overlapping objectives such as protecting at least 30% of the ocean[29]—which we show is not in conflict with smart aquaculture placement. As such, our results help to inform and guide how aquaculture would fit into the larger seascape of human uses, enabling integration into efforts to understand and map the cumulative impact of multiple human stressors[30,31] and as part of marine spatial planning efforts[32]. Furthermore, this analysis can be used in more comprehensive planning and evaluation frameworks, such as the Ocean Health Index[33], improving assessment and guidance on the role of aquaculture in the oceans to provide and interact with ocean benefits (for instance, ecosystem services). As aquaculture expands, integrating best-practice farming guidelines with spatially integrated assessments and indicators of ocean health and utilization could help guide marine aquaculture towards sustainable expansion.

Notably, many countries with the highest potential are not currently producing large quantities of marine aquaculture[34] (Fig. 4). For example, marine finfish production is concentrated in only a few countries, such as Norway, Chile and China, which have high potential for certain species but are not among the countries that we show have the highest biological growth potential across species. The species that show the most promise for open-ocean aquaculture are not the same species that are currently most common in marine farming[14], supporting the idea that future development may not occur in the areas that currently have the highest production. How the offshore industry develops, and which species become the most dominant will have clear repercussions for where aquaculture growth is most likely to occur.

The vast untapped aquaculture potential in much of the world and the mismatch between growth potential and current production suggests that other factors, such as social, economic, political and/or regulatory constraints are limiting aquaculture development far more than biological constraints or conflicting uses. Indeed, a gap between science, policy and local socioeconomic conditions appears to be a common problem limiting aquaculture expansion[26,35]. For example, regulatory inefficiency and uncertainty has contributed to limited marine aquaculture development in the United States, a country with high growth potential and large seafood markets mostly served by imports. While recent strides have been made to improve the permitting process in federal waters (notably the 2016 implementation of the Gulf of Mexico Fishery Management Plan for Offshore Aquaculture), significant social, economic and governance hurdles remain[36]. Furthermore, while large technological strides have been made to address issues that limit development, such as reliance on wild fish for feeds and difficulties anchoring cages and ropes in high seas, the economic reality of widespread open-ocean aquaculture is still to be demonstrated[37]. Future research and policy developments that integrate growth potential estimates with the economic and social aspects of aquaculture will provide further understanding of the potential growth trajectories and limits on marine aquaculture development across the world.

Given the breadth of locations that are potentially suitable for marine aquaculture, there is ample opportunity for well-managed development to increase resiliency to future environmental, social and economic shocks. Notably, some of the countries with the highest aquaculture growth potential are predicted to experience large population increases, such as India and Kenya[1] (Fig. 1 and Supplementary Table 3). In addition, four of the ten countries with the highest average GPI for finfish aquaculture are Pacific island nations, a region with both high fish consumption per capita and looming food security concerns[38,39]. It may be worthwhile for these high-potential, high-need countries to consider economic development opportunities by pursuing policies to enable marine aquaculture development. However, providing development incentives while ensuring sustainable development can be challenging. For example, Vietnam has pursued policies to encourage marine aquaculture growth, but still faces serious challenges related to environmental sustainability and technological infrastructure[40]. Overcoming these challenges will be essential for countries like Vietnam to achieve their aquaculture potential within a wider sustainability agenda. Additionally, the effects of aquaculture development on local food security can vary considerably[41–43] and continued research on the interactions between aquaculture policy and socially sustainable development is needed[35].

While our aquaculture suitability assessments were based on current ocean conditions, the environment is changing at an unprecedented rate[44]. Future efforts to assess how climate risks will modify this potential given predicted changes in regional ocean temperatures and productivity[44] will improve the long-term predictions of aquaculture potential and provide more nuanced assessments of how climate change will affect individual species. Nonetheless, given the relatively small amount of space needed for aquaculture to meet global and national seafood demands (especially if optimally sited), the breadth of physiological tolerances found across cultured species[20] and the ability of selective breeding to adapt organisms to future agroecosystems, the overarching conclusions of this paper are likely robust. Moving forwards, it will also be important to assess how different types of aquaculture affect and are affected by different climate scenarios.

Given the significant potential for marine aquaculture, it is perhaps surprising that the development of new farms is rare. Restrictive regulatory regimes, high costs, economic uncertainty, lack of investment capital, competition and limitations on knowledge transfer into new regions are often cited as impediments to aquaculture development[36,45]. In addition, concerns surrounding feed sustainability, ocean health and impacts on wild fisheries have created resistance to marine aquaculture development in some areas[13,46,47]. While ongoing and significant progress has been made in addressing sustainability issues with marine aquaculture[37], continued focus on these issues and dedication to ensuring best practices will be a crucial element shaping the future of marine aquaculture. Both the cultural and economic dimensions of development and the management and regulatory systems are critically important to understanding realistic growth trajectories and the repercussions of this growth. Our results show that potential exists for aquaculture to continue its rapid expansion, but more careful analysis and forward-thinking policies will be necessary to ensure that this growth enhances the well-being of people while maintaining, and perhaps enhancing, vibrant and resilient ocean ecosystems.

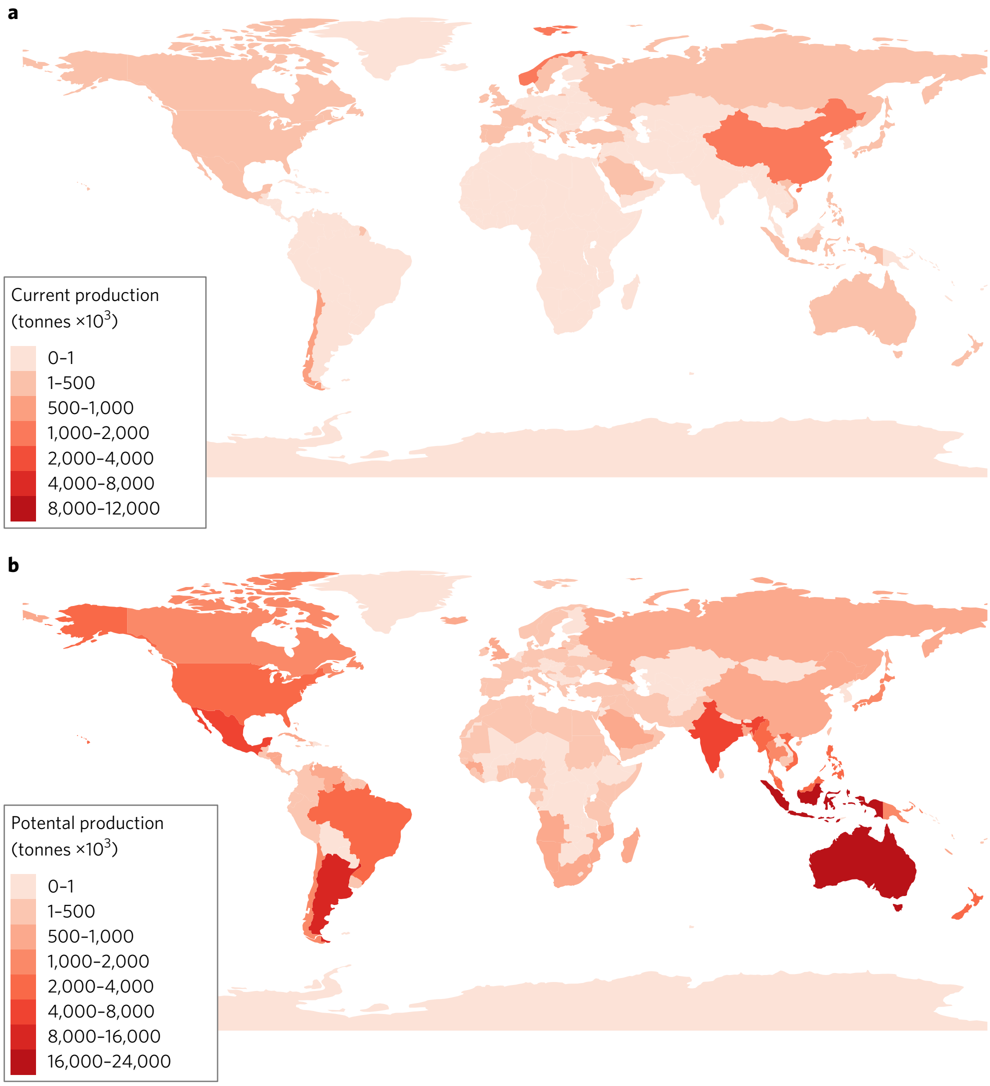

Fig. 4 | Marine aquaculture production and potential. **a**, Current marine aquaculture fish production. **b**, Potential production if 1% of the suitable area in each country was developed for low-density marine finfish aquaculture. Note that some countries, such as China and Norway, already produce more marine finfish than the projected potential, which could reflect more intensive production or a larger fraction of the marine area already developed for aquaculture.

Methods

Methodological approach and overview. To determine the relative productivity potential of ocean areas for marine aquaculture, we used an approach that considered the temperature tolerance of aquaculture species to estimate location-specific growth potential. We then used growth rate and allometric principles to estimate the potential annual production per unit area for both fish and bivalve aquaculture.

Finally, we constrained the suitable extent for fish and bivalve aquaculture to areas of allowable depth, environmental conditions and use restrictions. Globally, such constraints provide an initial, simplified framework for considering marine aquaculture development and represent only some of the key constraints that would be required for a more detailed regional analysis. In some cases, these constraints are likely to be conservative (for example, some existing uses could be moved to allow aquaculture to expand), whereas in other cases they are likely to be too liberal (for example, other factors such as ecological hotspots, current speeds or prime fishing zones would likely further limit the ideal aquaculture locations).

All analyses and visualizations were performed in R version 3.3.2 (ref. [48]) and the following packages were used: raster, rgdal, rasterVis, maps, dplyr, tidyr, ggplot2, RColorBrewer and ncdf4.

Calculating the growth performance index. *Species data and mapping.* A total of 180 consumable marine aquaculture-associated species were included in the analysis (120 fish and 60 bivalves). Information was collected on each species' temperature tolerance range (maximum and minimum temperature) and von Bertalanffy growth function (VBGF) parameters (K and Linf). All methods used for species selection are described in detail by Froehlich et al.[20] (see Supplementary Table 4 for a full list of included species and attributes).

Global sea surface temperature values (in °C) were used to map each species to the locations where they could potentially be grown, given their respective thermal limits. We note that other factors, such as intertidal versus open-ocean growing conditions may affect the suitability of individual species for culture in specific environments. To compare the range of temperatures in the marine environment to species' temperature tolerance ranges, we extracted annual maximum and minimum sea surface temperatures over a 30 year period (1982–2011). All sea surface temperature data were taken from the National Oceanic and Atmospheric Administration's World Ocean Atlas[49] at a resolution of 0.042 degrees. For each year and for each given unit area in the ocean, we determined which aquaculture species could tolerate the thermal environmental ranges in each location; all of the years were averaged to determine the mean number of fish and bivalve species that could be grown in each location (Supplementary Fig. 1). In general, temperate locations showed the highest numbers of potentially suitable species.

GPI calculation. The two VBGF parameters, $L\infty$ (asymptotic length of an organism where growth is zero) and K (growth rate), were then used to calculate the GPI for each species. The GPI is a single, unitless metric derived from the VBGF, which can be used to describe and compare the growth potential of species. It is most accurate when food is not constrained[21]. GPI values typically range between 0 and 5, with most aquaculture fish species exhibiting values above 2 (refs [23,24]). GPI (Φ') is described by the following equation:

$$\Phi' = \log_{10} K + 2\log_{10} L_\infty \quad (1)$$

For each unit area and each year, we calculated the average GPI across all species that were mapped to each given location. We then calculated the average for all years to obtain a mean GPI for each unit area (Supplementary Fig. 2). The s.d. of the GPI (Supplementary Fig. 3) gives an indication of the variability of GPI values for each location over time. In subsequent analyses, we removed areas for fish aquaculture that had an average GPI value below two, and for bivalves we removed areas with an average GPI value below one, as these did not have consistently warm enough water for commercial aquaculture development.

Sensitivity of the GPI. To determine the sensitivity of our global average GPI metric to species selection, we recreated the global average GPI maps with a reduced number of species. Specifically, instead of including all fish and bivalve species (the complete model), we took a bootstrap-like approach and created ten alternative scenarios in which we randomly selected (without replacement) half of the species and ran the same process of assigning species to locations based on temperature tolerance ranges. We calculated the average GPI for each location in the same way as described previously for the complete model. This allowed us to evaluate how species selection might affect overall patterns of growth potential.

To understand how the highest-production growing regions compared across these alternative models, we assessed whether specific locations that had the highest productivity (top 10%) in our complete model were also high productivity (top 20%) in our alternative models. A high percentage would indicate that the areas of high production were consistent across the complete and alternative models. For fish, we found high consistency between the complete model and the alternative model runs; across all alternative models, 90% of the highest-productivity areas from the complete model were in the top 20% of productivity areas in the alternative models (Supplementary Table 2). The bivalve model was not quite as robust to species selection, which is not surprising given the smaller sample size. On average, 60% of the highest-productivity bivalve areas from the complete model were captured in the top 20% of growing areas in the alternative models, but there was considerable variation between the different alternative scenarios, with many runs showing high consistency with the complete model and a few being extremely different.

We also compared the difference between GPI values in the complete model and each alternative model for every given location. We took the average of the differences from all the iterations to determine which locations are the most sensitive to species selection. The variation was fairly uniform for the fish model, but areas around Korea and the Middle East showed some increased variability, indicating a greater sensitivity of the GPI to species selection. For the bivalve model, high-latitude areas, such as the Gulf of California, the Gulf of Mexico and parts of the tropical Indo-Pacific showed elevated sensitivity to species selection (Supplementary Fig. 4). The already limited number of species that can occur in these thermal envelopes likely contributed to these results.

Constraint mapping. For each constraint, we set a threshold beyond which we would exclude aquaculture development. In general, we chose conservative thresholds for each of these variables, which resulted in the elimination of some areas that may be suitable for marine aquaculture. Each constraint layer, along with its source, resolution and threshold for aquaculture development, is listed in Supplementary Table 1. The areas found unsuitable for aquaculture for each constraint are shown in Supplementary Fig. 5. All layers were converted to geographical latitude and longitude coordinates. Our final map showing the potential productivity areas includes all regions with a minimum phi-prime score that were not eliminated due to any of the constraints. The original resolution of each constraint layer is noted in Supplementary Table 1; the final resolution of the potential production map is 0.0083 degrees, which is equivalent to the layer with the finest resolution (depth). Each constraint layer is described in more detail in the following paragraphs.

Depth. Most aquaculture operations are anchored to the seafloor, which becomes increasingly expensive as the depth increases[50]. We chose a maximum depth of 200 m, which we suggest reflects the outer bound of current industry practice. While aquaculture has taken place in deeper water and can even be free floating without any anchoring, we introduced this constraint to provide some economic realism to the analysis.

Dissolved oxygen. Low dissolved oxygen can be a significant problem for aquaculture operations, as it can cause reductions in fitness and ultimately death if the oxygen concentration is reduced far enough[51]. Low dissolved oxygen is a naturally occurring condition in some environments, but can be exacerbated by anthropogenic nutrient-producing activities, such as high-density fed aquaculture, terrestrial-based nutrient pollution and climate change[52]. While it is possible to increase the dissolved oxygen in a culture area through the use of aerators, it is generally preferable to avoid locations that commonly experience chronic low dissolved oxygen conditions.

We used dissolved oxygen data from the National Centers for Environmental Information, measured at a 30 m depth (since most aquaculture is grown below the surface) and averaged across all available decades (1921–2008); the data were too sparse to assess inter-annual variability. We assumed that chronic low dissolved oxygen would not be an issue in ocean areas with a depth of less than 30 m due to current and/or wind actions. All areas that had an annual average below the sub-lethal limit for fish (4.41 $mg\,l^{-1}$)[53] were excluded as potential aquaculture locations. This constraint led to a total of 1,041,975 km^2 (3.9% of the total area after constraining to 200 m depth regions) being removed from potential aquaculture areas (Supplementary Table 3). For bivalve aquaculture, we set the lethal limit at an annual average of less than 1.99 $mg\,l^{-1}$ (ref. [53]), which is the sub-lethal limit for molluscs. No areas fell below this threshold, so dissolved oxygen was not a constraining factor for bivalves.

Chlorophyll a concentration. Bivalve culture requires an adequate natural food supply for growth. Ideal growing environments have both a high and steady source of food to allow for continuous growth. While filter-feeding bivalves can obtain nutrition from a variety of sources, including detritus, the chlorophyll a concentration has been found to be a good proxy for food availability[54,55] and is the most robust available measurement on a global scale.

We used monthly average global chlorophyll a data from the Moderate Resolution Imaging Spectroradiometer satellites. Data from 2003 to 2014 were averaged to produce both a monthly and annual average concentration for each unit area. When no data were available for any given month (which occurred in high-altitude areas during winter), those months were excluded from the annual mean calculation.

The GPI metric is most accurate when food availability is not constrained; therefore, we limited bivalve growing regions to areas that have both high and consistent food availability. As a result, bivalve aquaculture areas were limited to regions that had annual chlorophyll a concentrations with an annual mean above 2 $mg\,m^{-3}$ and at least ten months with a chlorophyll a concentration greater than 1 $mg\,m^{-3}$. This constraint led to an additional total of 23,932,076 km^2 (89.5% of the total area after constraining to 200 m depth regions) being excluded from the potential aquaculture area.

These chlorophyll a requirements were drawn from existing publications and reports[56–58]. There were often missing satellite data for high-latitude locations during the winter months due to darkness and cloud cover; therefore, we allowed up to two months that did not to meet the 1 $mg\,m^{-3}$ threshold (that is, only 10 months with chlorophyll a values were required). This allowed some high-latitude areas to be included as suitable bivalve growing regions in our analysis without sacrificing the need for consistent food availability. Since our chlorophyll a requirements are quite conservative, this led to the exclusion of some areas that are successful existing bivalve growing regions. The success of bivalve farming outside our suitable areas may be attributable to growers who are able to create a profitable enterprise with relatively lower food availability (for example, semi-intensive culture) or may be because food sources, such as detritus, that were not captured by our data are relatively more important in certain regions.

Shipping traffic. Marine aquaculture operations are not compatible with heavy shipping traffic, and planning processes generally eliminate shipping lanes as potential locations for aquaculture[50,59]. We used data on global shipping intensity from Halpern et al.[31] to exclude the ocean areas with the highest shipping traffic. To do this, we divided the entire ocean area into 20 quantiles based on shipping intensity within each unit area. We then excluded aquaculture from the top 5% of the highest-intensity shipping areas. While 5% is only a small fraction of the total ocean area, it is disproportionately concentrated in the coastal areas (see Supplementary Fig. 5) and therefore has a significant effect on the total area available to aquaculture development. This constraint led to an additional total of 6,755,497 km^2 (25.3% of the total area after constraining to 200 m depth regions) being excluded from the potential aquaculture area.

Oil rigs. Oil rigs are used as an example of other ocean developments that in general exclude aquaculture. There have been some suggestions that aquaculture development could utilize inactive oil platforms, but developing aquaculture on an active oil platform remains unlikely[60]. Therefore, for this analysis we excluded all active oil rigs as locations for potential aquaculture development. Oil rig presence and absence data were taken from Halpern et al.[31]. This constraint led to an additional total of 680,126 km^2 (2.5% of the total area after constraining to 200 m depth regions) being excluded from the potential aquaculture area.

Marine protected areas. Marine protected areas vary substantially in their purpose and restrictions. For this analysis, we used data from the World Database on Protected Areas[61], which classifies protected areas into one of seven categories (Ia, Ib, II, III, IV, V or VI), which capture the primary stated management objectives of a marine protected area[62]. Categories V and VI are protected areas whose objectives explicitly acknowledge human interactions and resource use, so these areas were not excluded for marine aquaculture. However, the evaluation of whether aquaculture would be consistent with the objectives of these marine protected areas would need to be done on a local planning scale. The other five marine protected area categories focus primarily on conservation, so for these, aquaculture was excluded in our analysis. This constraint led to an additional total of 30,980 km^2 (0.1% of the total area after constraining to 200 m depth regions) being excluded from the potential aquaculture area. It is important to note that the current levels of marine protection are well below conservation targets and not representative spatially across the globe[63]. Therefore, the actual area that should be set aside for protection is likely to be larger than we applied in this analysis.

After all of these constraints were applied, the total area within continental shelf regions (depth < 200 m) was reduced from 26,748,980 km^2 to 11,402,629 km^2 for fish and 1,501,709 km^2 for bivalves.

Biomass calculations. To understand what the GPI means in terms of potential aquaculture biomass production, we used the VBGF and species-specific growth parameters to assess the amount of time it would take each aquaculture species used in our analysis to grow to a generic harvestable size. For fish, we estimated that the average marketable size is approximately 35 cm ('plate size'), and for bivalves we estimated that a marketable product would be approximately 4 cm long. Since nearly all aquaculture species reach these sizes, we were able to include the vast majority of species in the analysis. Including all species that reached our harvestable size, we used least squares regression to estimate how the GPI relates to time to harvest (Supplementary Fig. 6). To determine the most accurate functional form, we used hold-out sampling to remove 10% of the observations and then calculated the mean square error for linear, polynomial and exponential models. The chosen model had the lowest mean square error when the actual and estimated values were compared. The resulting equations are as follows:

$$\log(T_F) = 7.68 - 5.82 \times \log(\Phi') \quad (2)$$

$$\log(T_B) = 2.99 - 1.66 \times \Phi' \quad (3)$$

where T_F is the time for a fish to reach 35 cm and T_B is the time for a bivalve to reach 4 cm. The resulting R^2 values for these models were 0.90 and 0.88 for fish and bivalves, respectively.

For fish, we used principles of allometry to convert from length to weight[64]:

$$W = aL^b \quad (4)$$

where W is the weight, L is the length, and a and b are species-specific parameters. We used median values for a and b based on Froese[65], so that a = 3.025 and b = 0.01184. Using this equation, we determined that our generic 35 cm fish would weigh approximately 548 g at harvest.

The relationship between length and weight is quite variable across bivalve species[66], so we did not convert the potential production approximations to tonnage. Rather, we report potential production as the number of 4 cm individual bivalves.

To understand how the time to harvest estimation related to harvest per unit area, we assumed a consistent farm design for both fish and bivalve harvests. For fish, we assumed that each km^2 would contain 24 9,000 m^3 cages, each stocked with 20 juveniles per m^3. This low stocking density would result in a density at harvest of approximately 11 kg m^{-3}, which provides a conservative production per unit area estimate. For reference, the European organic standard maximum density is 15 kg m^{-3} for most marine finfish[67]. Farming densities for some marine fish can be up to or beyond 30 kg m^{-3} at harvest[68]. If a stocking density in this range was used, the production per unit area estimates in this study would nearly triple.

For bivalves, we based our design on the offshore longline growing of mussels, and assumed 100 long lines placed in each km^2 of the growing area. Each longline would have approximately 4,000 metres of fuzzy rope, and each foot of fuzzy rope would be seeded with 100 bivalves. The space required for anchoring would vary with depth and design, and was therefore not included in this analysis. We acknowledge that farm designs vary significantly and could be adjusted to meet local conditions; however, a uniform design allowed us to most clearly differentiate between areas on a global scale.

The production per unit area per year was calculated by dividing the total farm output by the number of years between stocking and harvest. This was based on the assumption that re-stocking would happen immediately post-harvest.

To calculate the overall production estimations, all potential aquaculture cells were rank-ordered by their average GPI value. The production for each cell and the total area of all cells were calculated as a running sum, thereby allowing for the assumption that the most productive locations would be developed first. Since our production maps are based on a latitude and longitude coordinate system, the resolution of each cell is equivalent in degrees latitude and longitude, but not in area. The variation in cell area was taken into consideration throughout the analysis, and all calculations of area and potential production accounted for the variability in cell size.

Country-level estimates and comparisons. Each unit area was assigned to a country based on the country and territory specifications used in Halpern et al.[33]. The average weighted GPI (the value for each cell weighted by its area) and the total developable area for each country and territory are listed in Supplementary Table 4. Consistent with the global production estimations, country production estimations also assumed sequential development of locations from the highest to lowest GPI.

The current aquaculture production and seafood consumption data came from the Food and Agricultural Organization and were extracted using the FishStatJ software[69].

Data availability. The data that support the findings of this study are available from the sources listed in Supplementary Table 1. All analyses, computer code and data products reported are publically accessible on the Knowledge Network for Bioclompexity data repository at https://doi.org/10.5063/F1CF9N69.

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Author contributions

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

Competing interests

The authors declare no competing financial interests.

Additional information

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