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No significant projected climate change effects on the geographic ranges of marine aquaculture species under the sustainable scenario (SSP 1-1.9, 1.5°C warming)

Amy Leigh Mackintosh[1] ✉, Griffin Goldstein Hill[1], Mark John Costello[1] & Jorge Assis[1,2]

Aquaculture is increasingly relied upon for global seafood production, projected to be the leading supplier by 2030. Climate change impacts on species health and industry productivity are already evident, creating uncertainties around long-term aquaculture development. While these impacts have been projected for some species, around 62% of aquaculture production remains unassessed. We utilized climate dissimilarity to assess the exposure of 327 species—including those previously unassessed—in their native ranges to changing climates under three climate scenarios: SSP1-1.9, SSP3-7.0, and SSP5-8.5. We projected that under a sustainability scenario (SSP1-1.9), 41% of Exclusive Economic Zones (EEZ) remained unexposed, including high-value aquaculture regions. However, under increased emissions scenarios (SSP3-7.0 and SSP5-8.5) all current aquaculture EEZ are projected to be exposed. Semi-enclosed seas, like the Baltic, Black, and Red Seas, experience the largest dissimilarity, alongside equatorial regions. Our findings suggest widespread mitigation efforts are necessary to ensure the long-term resilience of marine aquaculture.

Marine aquaculture is a critical component of global food security, accounting for almost one-third of global seafood production[1]. As the demand for seafood rises with increasing population, aquaculture is increasingly viewed as the future of seafood production[2]. However, climate change may constrain production directly, due to increases in pathogen prevalence, production losses, and damage to infrastructure, and indirectly, due to impacts on supply chains[3]. Consequently, we need to understand the impact of and exposure to climate change across aquaculture species and regions. This study provides the first global inventory of marine aquaculture (for our purposes, including coastal, offshore, and brackish water cultivation) species' exposure to climate change across a range of contrasting climate scenarios within the species native ranges.

Globally, most marine aquaculture production by live weight is made up of algae (51%, worth over 15 billion US$ in 2022). Not only does alga production contribute to food security, but it is also used in animal feeds, pharmaceutical products, and biofuels[4]. Algae production is followed by molluscs (26%, 30 billion US$), finfish (12%, 19 billion US$) and crustaceans (11%, 40 billion US$), with miscellaneous groups (including echinoderms and tunicates) contributing less than 1% of the total production and worth over 1.6 billion US$ in 2022[1]. More than 90% of production occurs in Asia, where more seafood was produced from aquaculture (both marine and freshwater) than from capture fisheries in 2022[1]. Even within Asia, marine aquaculture is unevenly distributed, with China leading production for each of the main species' groups[1,5,6]. Consequently, China has the highest economic value of total global aquaculture, followed by India, Indonesia, Vietnam and Norway[1]. This concentration of aquaculture production volume and economic value across a small number of countries has raised concerns over the long-term sustainability of the industry in a changing climate[7,8].

Increasingly evident in recent years, direct impacts of climate change affect marine aquaculture species' health and industry productivity, with both positive and negative effects already observed[9]. Ocean warming can lead to increased food conversion efficiencies and growth rates in some species[3,10,11]. However, it can also lead to stress and increased mortality

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[1]Faculty of Biosciences and Aquaculture, Nord University, Bodø, Norway. [2]Centre of Marine Sciences, CCMAR, University of Algarve, Faro, Portugal.
✉e-mail: amy.mackintosh@nord.no

where species' temperature tolerances are exceeded, particularly in cold-water species, even under limited warming of 2 °C[12,13]. The mass mortalities of Pacific threadfin (*Polydactylus sexfilis)* cultured in Hawaiian fishponds in 2009, triggered by a 2–3 °C ocean temperature increase during an El Niño Southern Oscillation event[14], exemplify the impacts such increases could have in the future. Additional environmental changes such as declining oxygen concentrations and changes in coastal salinity can stress aquaculture organisms, resulting in increased mortality events[15–17]. Though some land-based approaches may be shielded from these impacts, marine aquaculture remains largely reliant on ambient environmental conditions. While these chronic climate-related factors are projected to impact aquaculture, the only documented direct climate change-related effects on aquaculture to date have been due to marine heatwaves which have caused mass mortalities in marine aquaculture[18–20]. The diverse nature of these environmental changes, observed and projected, causes uncertainty regarding the overall impact of global climate change on marine aquaculture.

The growing threat of climate change to marine aquaculture has necessitated the development of models to assess global exposure to these changes. Initial models sought to anticipate the physiological responses of marine aquaculture species to temperature variations using growth rates and allometric principles[21]. Froehlich et al. utilized this model to project the marine aquaculture production potential of 120 finfish and 60 bivalve species to 2090 under the high emissions scenario only (RCP 8.5)[22]. Their findings suggested an expansion of suitable area for finfish, contrasted with a reduction for bivalves. However, including intermediate climate scenarios may show if impacts will occur before the high emissions scenario eventuates. The shared socio-economic pathway (SSP) scenarios encompass a wide spectrum of climate change futures, including a "sustainability" scenario (SSP1-1.9, 1.5 °C warming), a "regional rivalry" scenario (SSP3-7.0, 3.6 °C warming), and a "fossil fuel development" scenario (SSP5-8.5, 4.4 °C warming)[23,24]. Utilizing these scenarios, Oyinlola et al. projected increases in mariculture production for 55 finfish and bivalves under a sustainability scenario (SSP1-2.6, 1.8 °C warming) but decreases under a fossil fuel development scenario (SSP5-8.5), suggesting that without mitigation, climate change could become a major factor in marine aquaculture growth declines[25]. Overall, projections have been limited to finfish and bivalve species under, at most, two climate change scenarios. Algae, which constitute most of marine aquaculture biomass, and crustaceans, the most valuable per weight, along with other taxa, remain unassessed. Thus, about 62% of global marine aquaculture production, worth over 55 billion US$, has not been assessed for its sensitivity to climate change. Moreover, marine aquaculture is still expanding and species that are farmed today at one or a few locations may be farmed elsewhere in the future. Thus, marine aquaculture planning needs to have long-term projections of suitable conditions under future climate change and not remain limited to present production.

Here, we estimate the exposure of species of farmed algae, crustaceans, finfish, molluscs, tunicates, and echinoderms, in their native ranges to changing climate conditions under three distinct climate scenarios: SSP1-1.9, SSP3-7.0, and SSP5-8.5. Several important species, such as Atlantic and Pacific salmonids in Chile, Tasmania and Canada, as well as cupped oyster and Manila clams in Europe, are being farmed outside their native range, and these distributions are excluded from our analysis. However, most species are farmed within their native range, and this is likely to be prioritized in the future due to concerns over the spread of non-native species. In this way, emphasis is placed upon the conditions under which marine aquaculture is most easily implemented—through the cultivation of existing aquaculture species within their native ranges. The climate dissimilarity index quantifies the differences between two distinct climates[26,27] and considers various climatic variables to identify similar climates across space and time (i.e., analogous). Exposure of species to climate dissimilarity (conditions outside of their current climates), but within their native ranges, is quantified via the index mean and the proportion of local marine aquaculture species impacted[28]. This approach has already served as an important tool to aid conservation planners, policymakers and industry stakeholders in planning for the impacts of climate change and developing mitigation strategies, particularly regarding terrestrial climates and marine protected area resilience[29,30]. Additionally, we aim to assess regional vulnerability as a function of potential exposure and current aquaculture value per Exclusive Economic Zone (EEZ). By including all commercial marine aquaculture species across their native ranges, regardless of current cultivation importance, we capture the contrasting consequences of climate change on marine aquaculture species across a spectrum of SSP scenarios, highlighting the established and emerging marine aquaculture species and regions that are most exposed to climate dissimilarity.

Results

The modeled natural distribution of the 327 marine aquaculture species (Table 1) showed that species richness was the highest in Japan, China, Southeast Asia, Australia, and India (Fig. 1), with the number of marine aquaculture species' native ranges per EEZ ranging from 1 to 169. Additionally, the highest species richness per group was observed in the same regions (Fig. 2). In total, dissimilarity was assessed across 265 EEZ, of which 127 are current marine aquaculture producers.

Sustainability scenario

In a sustainability scenario (SSP1-1.9), adhering to the Paris Agreement, cells that were projected to be exposed to climate dissimilarity were largely within the northern hemisphere, with Svalbard and the Kuril Islands being the only EEZ exposed to extreme dissimilarity on average (Figs. 3, 4B, C; Table S1). Of the 127 EEZ with current marine aquaculture, 17% ($n = 22$) were projected to experience climate dissimilarity ($\sigma \geq 2$; Table 2; Table S1). Additionally, crustaceans, echinoderms and tunicates were projected to remain unexposed to climate dissimilarity (Figs. S1 and S4). Lastly, 41% of all EEZ ($n = 108$) remained unexposed to climate dissimilarity ($\sigma = 0$) (Table S2).

Regional rivalry scenario

Under a regional rivalry climate change scenario (SSP3-7.0), 2% ($n = 4$) of all EEZ remained unexposed to projected climate dissimilarity ($\sigma = 0$; Table S2), 64% ($n = 171$) of all EEZ faced moderate exposure ($\sigma \geq 2$), and 21% ($n = 56$) faced extreme exposure ($\sigma \geq 4$). Kerguelen and Bermuda recorded the highest mean dissimilarity, followed by EEZ within semi-enclosed marine regions which are partly enclosed by land: Lithuania, Latvia, Georgia and Poland (Fig. 4E). Mean projected dissimilarity by hexagonal cells identified New Zealand and equatorial regions, including south-east Asia and the Caribbean, as experiencing extreme dissimilarity ($\sigma \geq 4$; Figs. 3, 4D, F). The Arctic, Baltic Sea, Black Sea and south-east Asia had the highest proportion of species per hexagon exposed to climate dissimilarity (Fig. 5), with all taxonomic groups represented (Figs. S2 and S5). South-east Asia had the highest proportion of global species exposed to dissimilar climates (Fig. S7). Among current marine aquaculture EEZ, 96% ($n = 123$) were projected to experience climate dissimilarity ($\sigma \geq 2$; Table 2; Table S1). Only the Matthew and Hunter Islands, the San Felix and San Ambrosio Islands, Easter Island, and the Prince Edward Islands EEZ were not exposed to climate dissimilarity ($\sigma = 0$; Table S2).

Fossil fuel development scenario

Projections of a fossil fuel development climate scenario (SSP5-8.5) revealed several regions with all resident marine aquaculture species exposed to dissimilar climates including the Arctic, semi-enclosed regions, and equatorial regions (Fig. 5). Only 1% ($n = 3$) of all EEZ remained unexposed to climate dissimilarity ($\sigma = 0$), while 48% ($n = 127$) faced moderate exposure ($\sigma \geq 2$), and 44% ($n = 116$) faced extreme exposure ($\sigma \geq 4$). Notably, the highest mean dissimilarities were concentrated along the equator and within semi-enclosed regions such as the Baltic, Black, and Red Seas, and the Persian Gulf (Figs. 3, 4G, H, I). Equatorial regions, semi-enclosed regions, and the Arctic were also projected to have the highest proportion of species exposed to climate dissimilarity (Fig. 5), with all taxonomic groups represented (Figs. S3 and S6). Globally, the highest proportion of species impacted was concentrated throughout South-east Asia, India and northern

Table 1 | List of 327 marine aquaculture species assessed in this study, categorized into six taxonomic groups: algae, crustaceans, echinoderms, finfish, molluscs, and tunicates

Algae (23)			
Alaria esculenta	*Eucheuma denticulatum*	*Macrocystis pyrifera*	*Saccharina japonica*
Capsosiphon fulvescens	*Gelidium amansii*	*Meristotheca senegalense*	*Saccharina latissima*
Caulerpa racemosa	*Gracilaria gracilis*	*Monostroma nitidum*	*Sargassum fusiforme*
Chondracanthus chamissoi	*Gracilariopsis longissima*	*Palmaria palmata*	*Ulva prolifera*
Cladosiphon okamuranus	*Kappaphycus alvarezii*	*Pyropia columbina*	*Undaria pinnatifida*
Codium fragile	*Laminaria digitata*	*Pyropia tenera*	
Crustaceans (35)			
Acetes japonicus	*Palaemon adspersus*	*Penaeus japonicus*	*Penaeus stylirostris*
Artemia salina	*Palaemon serratus*	*Penaeus kerathurus*	*Penaeus vannamei*
Callinectes sapidus	*Palaemonetes varians*	*Penaeus merguiensis*	*Portunus pelagicus*
Carcinus aestuarii	*Panulirus argus*	*Penaeus monodon*	*Portunus trituberculatus*
Carcinus maenas	*Panulirus japonicus*	*Penaeus penicillatus*	*Scylla olivacea*
Maja squinado	*Panulirus polyphagus*	*Penaeus plebejus*	*Scylla paramamosain*
Metapenaeus ensis	*Penaeus chinensis*	*Penaeus schmitti*	*Scylla serrata*
Metapenaeus macleayi	*Penaeus esculentus*	*Penaeus semisulcatus*	*Thenus orientalis*
Metapenaeus monoceros	*Penaeus indicus*	*Penaeus setiferus*	
Echinoderms (3)			
Apostichopus japonicus	*Loxechinus albus*	*Paracentrotus lividus*	
Finfish (164)			
Acanthopagrus berda	*Caranx hippos*	*Diplodus sargus sargus*	*Helicolenus dactylopterus*
Acanthopagrus bifasciatus	*Caranx ignobilis*	*Diplodus vulgaris*	*Hexagrammos otakii*
Acanthopagrus latus	*Caranx sexfasciatus*	*Dormitator latifrons*	*Hippoglossus hippoglossus*
Acanthopagrus schlegelii	*Centropomus undecimalis*	*Eleutheronema tetradactylum*	*Huso huso*
Acipenser stellatus	*Centropristis striata*	*Ellochelon vaigiensis*	*Hyporthodus septumfasciatus*
Anarhichas lupus	*Chaetodipterus faber*	*Emmelichthys nitidus*	*Konosirus punctatus*
Anarhichas minor	*Chanos chanos*	*Epinephelus akaara*	*Larimichthys crocea*
Anguilla anguilla	*Chelon auratus*	*Epinephelus areolatus*	*Lateolabrax japonicus*
Anguilla australis	*Chelon saliens*	*Epinephelus awoara*	*Lates calcarifer*
Anguilla bicolor bicolor	*Coregonus lavaretus*	*Epinephelus bruneus*	*Lethrinus miniatus*
Anguilla japonica	*Crenimugil seheli*	*Epinephelus chlorostigma*	*Liza ramada*
Anguilla rostrata	*Cromileptes altivelis*	*Epinephelus coioides*	*Lutjanus argentimaculatus*
Anoplopoma fimbria	*Decapterus macrosoma*	*Epinephelus corallicola*	*Lutjanus bohar*
Argyrosomus hololepidotus	*Dentex dentex*	*Epinephelus fuscoguttatus*	*Lutjanus erythropterus*
Argyrosomus japonicus	*Dentex gibbosus*	*Epinephelus lanceolatus*	*Lutjanus goldiei*
Argyrosomus regius	*Dentex tumifrons*	*Epinephelus malabaricus*	*Lutjanus guttatus*
Atherina boyeri	*Dicentrarchus labrax*	*Epinephelus tauvina*	*Lutjanus johnii*
Bolbometopon muricatum	*Dicentrarchus punctatus*	*Epinephelus tukula*	*Lutjanus malabaricus*
Boleophthalmus pectinirostris	*Diplodus puntazzo*	*Gadus morhua*	*Lutjanus purpureus*
Carangoides malabaricus	*Diplodus sargus*	*Gnathanodon speciosus*	*Lutjanus russelli*
Lutjanus sebae	*Pagrus auratus*	*Rhabdosargus sarba*	*Siganus rivulatus*
Megalops atlanticus	*Pagrus auriga*	*Salmo salar*	*Siganus sutor*
Melanogrammus aeglefinus	*Pagrus caeruleostictus*	*Salmo trutta*	*Solea senegalensis*
Micropogonias furnieri	*Pagrus major*	*Salvelinus alpinus*	*Solea solea*
Miichthys miiuy	*Pagrus pagrus*	*Schedophilus ovalis*	*Sparidentex hasta*
Morone saxatilis	*Paralichthys microps*	*Sciaena umbra*	*Sparus aurata*
Mugil cephalus	*Paralichthys olivaceus*	*Sciaenops ocellatus*	*Symphysanodon berryi*
Mugil curema	*Planiliza haematocheilus*	*Scomber japonicus*	*Synodus marchenae*
Mugil liza	*Planiliza macrolepis*	*Scophthalmus maximus*	*Takifugu rubripes*
Muraenesox cinereus	*Platax orbicularis*	*Scophthalmus rhombus*	*Terapon jarbua*
Mycteroperca bonaci	*Platichthys flesus*	*Sebastes schlegelii*	*Thunnus albacares*

Table 1 (continued) | List of 327 marine aquaculture species assessed in this study, categorized into six taxonomic groups: algae, crustaceans, echinoderms, finfish, molluscs, and tunicates

Algae (23)			
Oncorhynchus gorbuscha	*Plectropomus maculatus*	*Sebastiscus marmoratus*	*Thunnus maccoyii*
Oncorhynchus keta	*Pleurogrammus azonus*	*Seriola dumerili*	*Thunnus orientalis*
Oncorhynchus kisutch	*Pleuronectes platessa*	*Seriola lalandi*	*Thunnus thynnus*
Oncorhynchus masou	*Pollachius pollachius*	*Seriola quinqueradiata*	*Tilapia guineensis*
Oncorhynchus mykiss	*Polydactylus sexfilis*	*Seriola rivoliana*	*Trachinotus blochii*
Oncorhynchus nerka	*Pomatomus saltatrix*	*Siganus canaliculatus*	*Trachinotus carolinus*
Oncorhynchus tshawytscha	*Psammoperca waigiensis*	*Siganus fuscescens*	*Trachinotus goodei*
Oplegnathus fasciatus	*Pseudocaranx dentex*	*Siganus guttatus*	*Trachinotus ovatus*
Pagellus bogaraveo	*Pseudopleuronectes americanus*	*Siganus javus*	*Trachurus japonicus*
Pagellus erythrinus	*Rachycentron canadum*	*Siganus lineatus*	*Umbrina cirrosa*
Molluscs (101)			
Aequipecten opercularis	*Ensis directus*	*Mercenaria mercenaria*	*Pecten jacobaeus*
Aliger gigas	*Ensis ensis*	*Meretrix lusoria*	*Pecten maximus*
Anadara broughtonii	*Gomphina veneriformis*	*Meretrix meretrix*	*Perna canaliculus*
Anadara kagoshimensis	*Haliotis discus*	*Metasepia tullbergi*	*Perna perna*
Anadara tuberculosa	*Haliotis discus hannai*	*Mimachlamys crassicostata*	*Perna viridis*
Argopecten irradians	*Haliotis diversicolor*	*Mimachlamys varia*	*Pinctada fucata*
Argopecten purpuratus	*Haliotis iris*	*Mizuhopecten yessoensis*	*Pinctada margaritifera*
Argopecten ventricosus	*Haliotis midae*	*Mya arenaria*	*Pinctada maxima*
Asaphis violascens	*Haliotis rufescens*	*Mytilus chilensis*	*Placopecten magellanicus*
Aulacomya ater	*Haliotis tuberculata*	*Mytilus coruscus*	*Polititapes aureus*
Babylonia areolata	*Hiatula diphos*	*Mytilus edulis*	*Polititapes rhomboides*
Bolinus brandaris	*Hippopus hippopus*	*Mytilus galloprovincialis*	*Pteria penguin*
Cerastoderma edule	*Larkinia grandis*	*Mytilus planulatus*	*Ruditapes decussatus*
Cerastoderma glaucum	*Leukoma staminae*	*Mytilus platensis*	*Ruditapes philippinarum*
Chamelea gallina	*Mactra glabrata*	*Nodipecten subnodosus*	*Saccostrea cucullata*
Chlamys farreri	*Mactra quadrangularis*	*Ostrea chilensis*	*Saccostrea glomerata*
Choromytilus chorus	*Magallana angulata*	*Ostrea conchaphila*	*Saxidomus gigantea*
Concholepas concholepas	*Magallana ariakensis*	*Ostrea edulis*	*Scapharca cornea*
Crassostrea corteziensis	*Magallana belcheri*	*Ostrea lurida*	*Scrobicularia plana*
Crassostrea rhizophorae	*Magallana bilineata*	*Panopea generosa*	*Sepia officinalis*
Crassostrea tulipa	*Magallana gigas*	*Paphia gallus*	*Sinonovacula constricta*
Crassostrea virginica	*Magallana rivularis*	*Paratapes undulatus*	*Tegillarca granosa*
Cyclina sinensis	*Magallana sikamea*	*Pecten fumatus*	*Tresus nuttallii*
Tridacna crocea	*Tridacna maxima*	*Turbo setosus*	
Tridacna derasa	*Tridacna squamosa*	*Venerupis corrugata*	
Tridacna gigas	*Turbo cornutus*	*Venus verrucosa*	
Tunicates (1)			
Pyura stolonifera			

Australia (Fig. S7). Additionally, 98% ($n = 125$) of current marine aquaculture EEZ were projected to experience climate dissimilarity ($\sigma \geq 2$; Table 2; Table S1).

Exposure by marine aquaculture value and mean dissimilarity

Under a sustainability scenario, categorization based on projected climate dissimilarity and 2021 marine aquaculture production value placed 3 EEZ in the Develop quadrant and 19 EEZ in the Optimize quadrant, characterized by moderate dissimilarity compared to relatively high marine aquaculture investment (Fig. 6). Crustaceans, echinoderms and tunicates were not represented as they did not experience climate dissimilarity in this scenario.

In the regional rivalry scenario, EEZ were primarily categorized between the Develop and Optimize quadrants (43 and 75 EEZ, respectively), with 28 EEZ in the Mitigate quadrant (Fig. 6). Notably, finfish in Georgia and molluscs in Lithuania were the most exposed but with low EEZ marine aquaculture value, thus falling into the Adapt quadrant alongside 14 other EEZ. Bangladesh had high marine aquaculture value, with high dissimilarity of algae categorizing it into the Mitigate quadrant. China was separated from most EEZ in the Optimize quadrant by its exceptional marine aquaculture value across taxa.

The number of EEZ in the Mitigate quadrant increased under the fossil fuel development scenario to 51. The majority of EEZ fell within the Optimize category, decreasing to 73 (Fig. 6). The number of EEZ in the

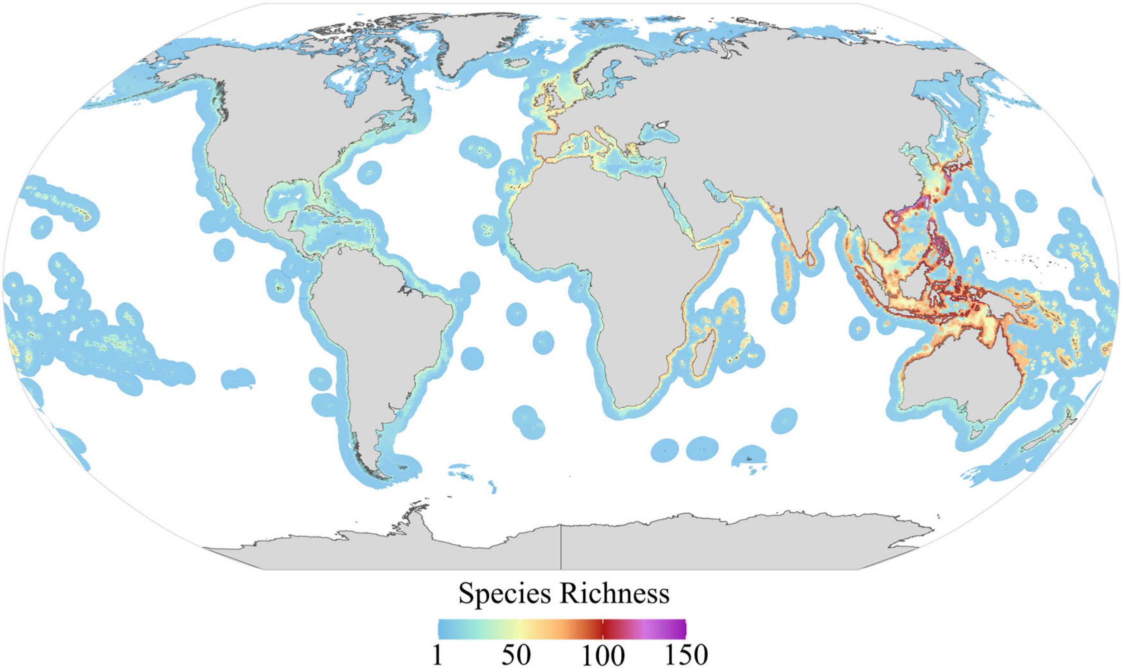

Fig. 1 | The global native species richness of the 327 marine aquaculture species considered in this study. Blue represents low marine aquaculture species richness, while purple represents high species richness. In total, 265 EEZ are included, with colored areas composed of equal-area hexagonal cells (approximately 50 km cell spacing) that aggregate the model output.

Adapt quadrant increased to 34, while the number in the Develop quadrant increased to 39. Of the most exposed EEZ as ranked by dissimilarity and marine aquaculture value, most fell within the Mitigate quadrant. Finfish in Georgia and molluscs in Lithuania were the only highlighted points with extreme climate dissimilarity in the Adapt quadrant, reflecting high exposure of a relatively small national marine aquaculture industry.

Discussion

This study demonstrates that global marine aquaculture production could remain largely unimpacted by climate change under the sustainability scenario that aligns with the Paris Agreement (i.e., 1.5 °C warming). Here, 40% of all EEZ remained entirely unexposed to climate dissimilarity. Similarly, crustaceans, echinoderms and tunicates, comprising 11% of global marine aquaculture production[31] were projected to remain unexposed. Under increased emissions scenarios, our results highlighted development challenges in semi-enclosed marine regions, currently viewed as candidates for future marine aquaculture, due to changing climates. Moreover, our results reinforced that marine aquaculture throughout equatorial regions is increasingly impacted under the increased emissions scenarios.

Climate dissimilarity advances the findings of previous studies by Froehlich et al. and Oyinlola et al. that, even in an extreme climate change scenario, marine aquaculture can maintain production for countries identified as major aquaculture producers by the FAO, such as China, Vietnam, Indonesia, and the Philippines[22,25]. Though the hexagonal cells comprising our results are larger than any single farm (approximately 50 km cell spacing), they provide information at a sub-EEZ unit useful for the regional management of marine aquaculture and designation of areas for farming. Two studies based on the biophysical models developed by Gentry et al. found that the profitable area for marine aquaculture was not forecast to appreciably decline, except for bivalves[21], and that strategic siting of new farms within EEZ was sufficient to avoid adverse climate impacts[32,33]. This is consistent with our finding that areas of low dissimilarity exist within the EEZ of major producers, even under SSP5-8.5. These results build upon previous studies through the inclusion of a wider array of species and climate change scenarios, globally and at a regional resolution for all countries, including regions without existing marine aquaculture.

Under the sustainability climate scenario, 27% of the EEZ that are unexposed to climate dissimilarity are present-day marine aquaculture-producing nations, assuming the continuation of current species and production for future marine aquaculture. Major contributors include Indonesia and the Philippines, ranked among the top global producers of finfish, crustaceans and algae[1]. Both countries are also major consumers of seafood with declining capture fisheries and plans for marine aquaculture expansion[34–36]. While marine aquaculture in these regions may remain unimpacted under this scenario, it experiences changing climates under increased emissions scenarios[37].

The EEZ that experience dissimilarity (>2) are all categorized within Develop or Optimize (Fig. 6). Major producers such as China, India, and Chile are categorized under Optimize, reflecting their robust and established marine aquaculture industries and suggesting that they could refine their practices in preparation for environmental changes. Despite China's leading position in global aquaculture, continuous improvement in practices and policy is essential to maintain this position and promote the sustainable development of marine aquaculture in the face of climate change[38,39]. Technology investments, selective breeding, and enhanced climate forecasting may be essential for strengthening industry resilience[40,41]. Recognizing the potential of unimpacted EEZ to serve as productive environments for marine aquaculture expansion, high-value producers may play a crucial role in determining the trajectory of marine aquaculture growth globally.

Previously unassessed species groups (crustaceans, echinoderms and tunicates), representing over 10% of current marine aquaculture and worth over US$56 million, remain unexposed under a sustainability scenario. Species exposed to changing environments are primarily concentrated in the Northern Hemisphere, specifically Arctic regions, highlighting the rate at which the Arctic is changing in comparison to the rest of the global marine environment[42]. Indeed, projected biodiversity shifts are estimated to exceed thresholds previously observed[43,44]. Increasing ocean temperatures at high latitudes may lead to increased growth rates of marine aquaculture species, particularly fed finfish and crustaceans[45–47]. Lavin et al. found five Arctic fish

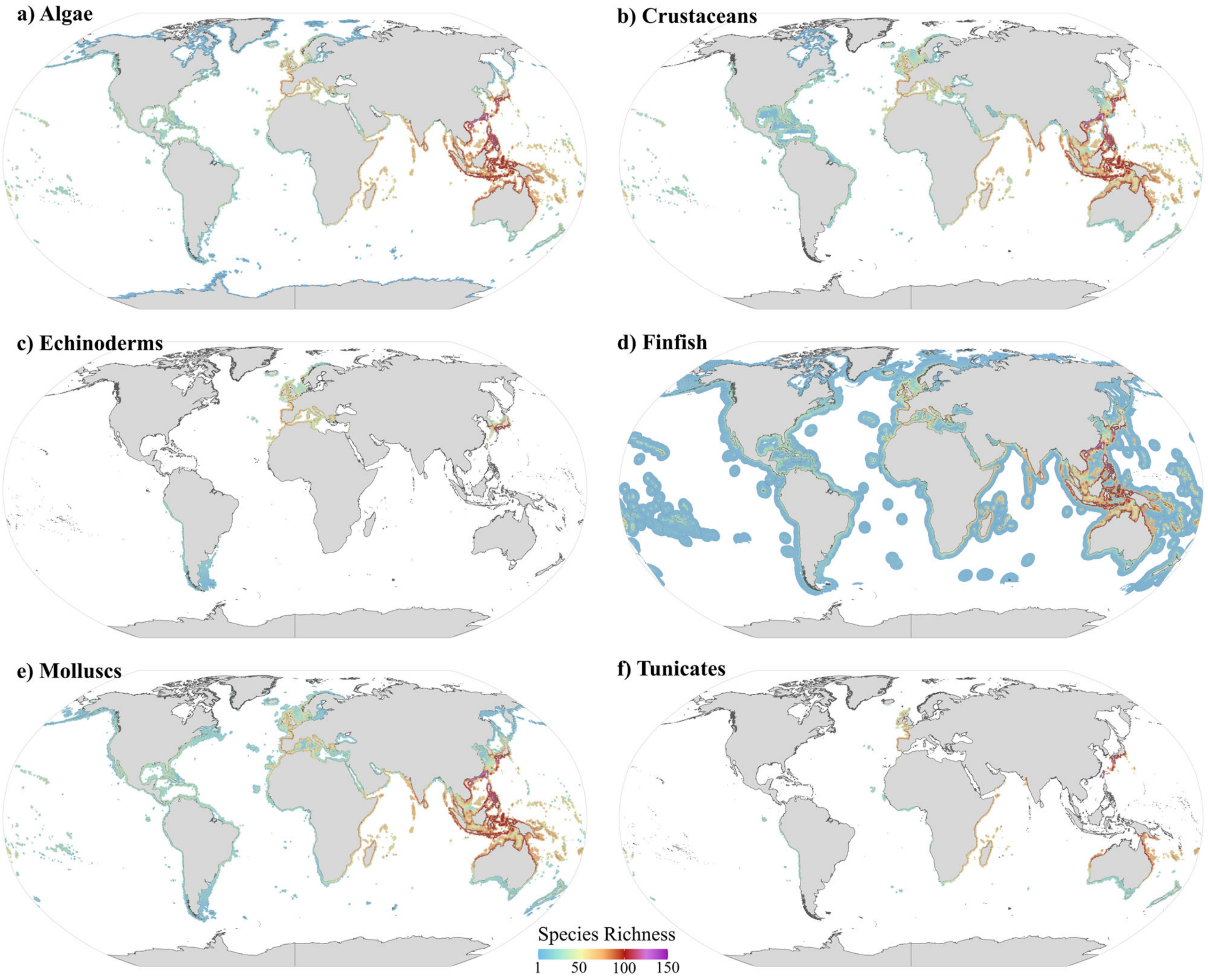

Fig. 2 | The native species richness of each of the aquaculture taxonomic groups used in this analysis. This included algae (**a**, $n = 23$), crustaceans (**b**, $n = 35$), echinoderms (**c**, $n = 3$), finfish (**d**, $n = 164$), molluscs (**e**, $n = 101$), tunicates (**f**, $n = 1$). Blue represents low marine aquaculture species richness, while purple represents high species richness. In total, 265 EEZ are included, with colored areas composed of equal-area hexagonal cells (approximately 50 km cell spacing) that aggregate the model output.

species were growing larger, and probably faster, due to ocean warming[48]. This could benefit marine aquaculture production if temperatures remain within the species' thermal tolerance[49,50]. However, the impacts on feed conversion efficiency in finfish will likely be mixed over the production cycle and deoxygenation may limit maximum body size and animal health at desirable harvest sizes[48,51–54]. However, as the Paris Agreement warming threshold of 1.5 °C was surpassed in 2024, it seems unlikely that the end-of-century climate will resemble this scenario[55].

Under increased emissions scenarios, all EEZ with existing marine aquaculture were projected to experience changing climate conditions. However, many EEZ contained regions with low dissimilarity at a localized (hexagonal cell) scale, indicating pockets of resilience within EEZ. This includes major producers such as China, Indonesia, Chile, Norway, and India – all countries with average dissimilarity above 2.5 under increased emissions. This suggests that while leading species and countries in global aquaculture may remain largely unchanged, regional adaptation and within-country relocation of marine aquaculture may be necessary. When EEZ are ranked using an extremity weighting—considering marine aquaculture value and climate dissimilarity—most of these top producers, except Chile and Norway, rank among the top 10. Many of them fall within the Mitigate category, further emphasizing the need for proactive measures such as relocation and resilience enhancement. These strategies could help reduce climate exposure in countries with high production, shifting existing investment from a potential liability to an advantage[56].

Our research found that marine aquaculture in semi-enclosed regions may be disproportionately impacted by climate change. Specifically, marine aquaculture species distributed within the Baltic, Black, and Red Seas are likely to experience the highest rates of climate dissimilarity, on average. These findings are supported by previous studies that have observed and projected the increased rate of warming in semi-enclosed regions, especially along the coast where the strongest warming is projected[57–59]. However, as marine aquaculture makes up a small percentage of these countries' gross domestic product, changing environments for marine aquaculture species may not negatively impact these nations, but rather limit the industry's expansion potential. In the Baltic, for example, plans to scale up marine aquaculture activity are already in place as part of the EU Strategy for the Baltic Sea Region, to both produce food and reduce the nutrient load in the system, but may not actually be feasible in the long-term at the proposed scale due to climate change[60,61].

Our findings also confirm that equatorial regions will be increasingly impacted by climate dissimilarity as climate scenarios worsen. The accelerated rate of change projected for the equatorial region is not only reinforced by numerous studies[43,62,63] but is also currently being observed, particularly through species range shifts[64,65]. Many marine species

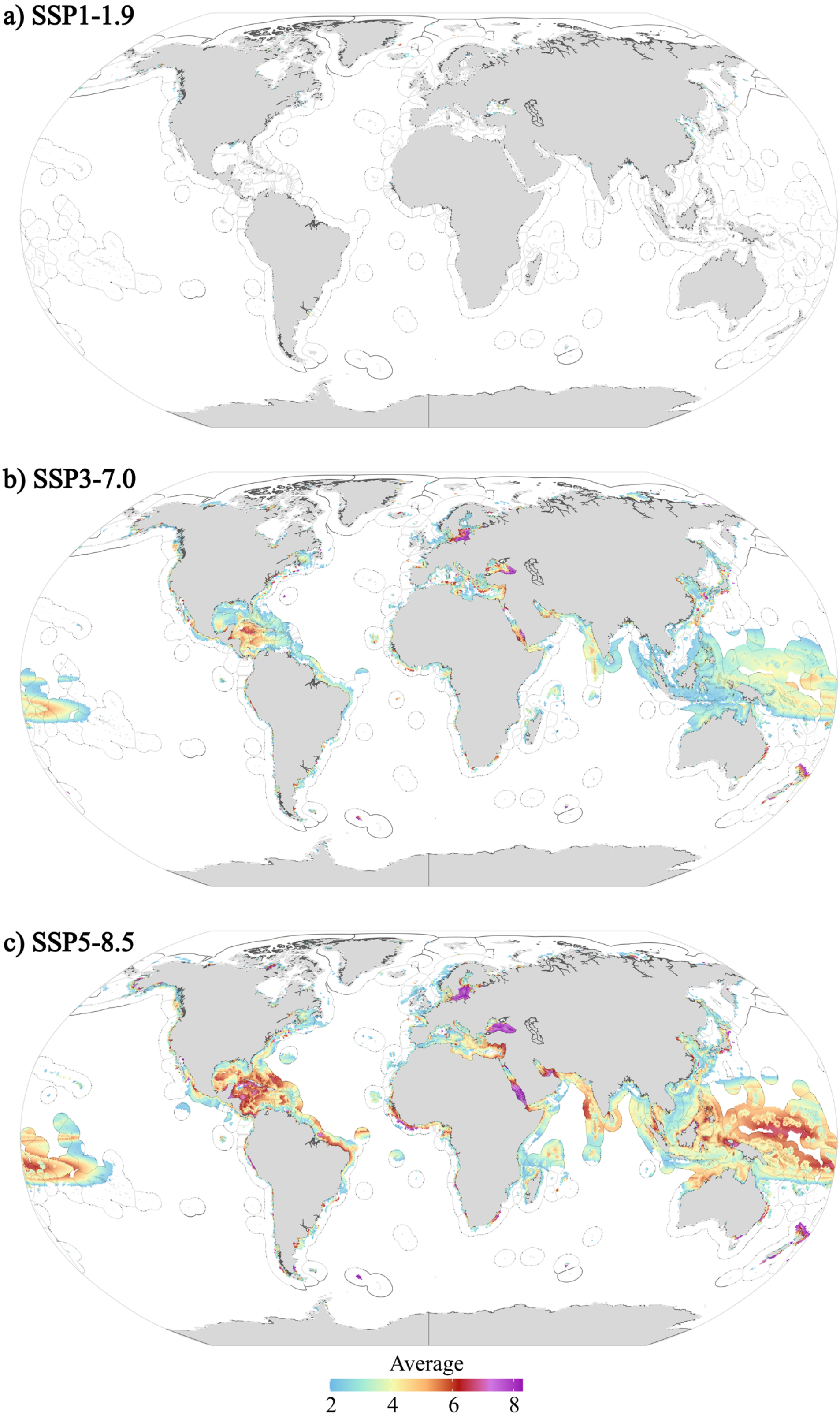

Fig. 3 | The mean climate dissimilarity for all marine aquaculture species per cell. Cells with a climate dissimilarity >2 are represented under three climate change scenarios: SSP1-1.9 (**a**), SSP3-7.0 (**b**), and SSP5-8.5 (**c**). Values <2 represent similar climates, 2–4 represent moderately dissimilar climates, and >4 represent extreme dissimilar climates. In total, 265 EEZ are included, with colored areas composed of equal-area hexagonal cells (approximately 50 km cell spacing) that aggregate the model output.

distributed within tropical equatorial habitats live at the upper limits of their already narrow thermal safety margins and are therefore highly vulnerable to further rising temperatures[43,66]. This is especially important given the dominance of tropical and subtropical regions in current marine aquaculture production[5]. The transition to more resilient strains and/or species is already occurring in select regions[67–69] but may not track the rate at which climate change renders traditional local cultivars non-viable. Based on our results, marine aquaculture development in equatorial and semi-enclosed seas, without significant climate mitigation, may struggle to increase food security and economic prospects from the marine aquaculture activities.

Despite the prevalence of projected impacts under increasing emissions, some EEZ remain unexposed to dissimilarity. In a regional rivalry

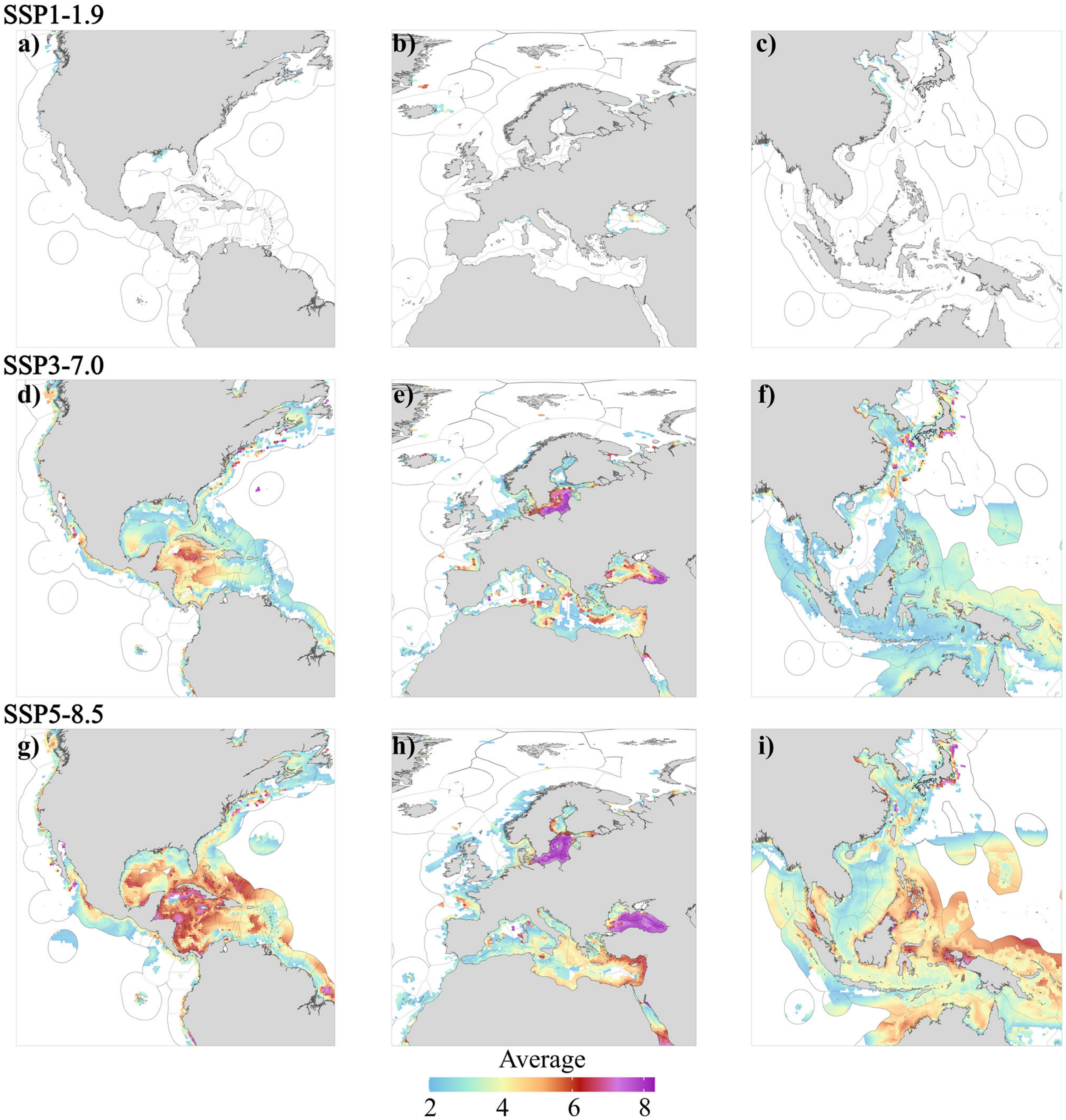

Fig. 4 | Regional maps of mean climate dissimilarity for marine aquaculture species under three climate change scenarios (SSP1-1.9, SSP3-7.0, SSP5-8.5). Panels show enlarged views of (**a**, **d**, **g**) the tropical Americas, (**b**, **e**, **h**) Europe and the Mediterranean, and (**c**, **f**, **i**) Southeast and East Asia, respectively. Colors represent the mean dissimilarity per cell, consistent with the global map in Fig. 3. Only cells with a dissimilarity >2 are shown; values between 2 and 4 represent moderate climate dissimilarity and >4 indicate extreme dissimilarity relative to current conditions. In total, 265 EEZ are included, with colored areas composed of equal-area hexagonal cells (approximately 50 km cell spacing) that aggregate the model output.

scenario, four EEZ were unexposed and, in a worst-case scenario, three of those four remain unexposed. Of these four EEZ, only Easter Island is permanently inhabited by a civilian population that relies on small-scale traditional and artisanal fisheries for seafood supply[70]. Despite the potential resilience of future cultivation to climate change, there are no plans to develop marine aquaculture at these locations. Other EEZ fall into the Develop category, characterized by low aquaculture value facing relatively low climate dissimilarity, representing potential opportunities for marine aquaculture growth and are approximately equally prevalent under the two higher emissions scenarios. Members of this group represent opportunities to achieve the necessary contribution of sustainable aquaculture to global food security[71], demonstrating unrealized production capacity in countries such as Argentina, Pakistan, and Tuvalu that is not projected to be hindered by climate change. Of these highlighted for development potential by the model, Argentina has recently developed a farmed trout industry in coastal waters, while Pakistan and Tuvalu have highlighted the potential of their extensive coastlines, but do not have existing marine aquaculture activities[72]. Overall, the addition of a weighted extremity metric and strategic categories to the traditional framework of regional classification based on vulnerability is applicable to a variety of model results. This approach improves the accessibility of analytical findings and has the potential to aid in the communication of model outcomes to stakeholders looking to tailor adaptation

Table 2 | The 20 Exclusive Economic Zones (EEZ) with the highest aquaculture value in billion US dollars for 2021 and the average climate dissimilarity and proportion of species impacted for each, under three climate scenarios

Exclusive Economic Zone (EEZ)	Aquaculture Value 2021 (billion US$)	SSP1-1.9		SSP3-7.0		SSP5-8.5	
		Average	Proportion	Average	Proportion	Average	Proportion
China	56.19	2.91	0.25	3.25	0.89	3.18	0.99
Vietnam	9.37	2.05	0.01	2.94	0.39	2.94	0.94
Norway	9.33	-	-	2.95	0.84	3.10	0.92
Chile	9.01	2.44	0.33	3.14	0.47	3.27	0.49
Indonesia	7.88	-	-	2.88	0.77	4.11	0.96
India	5.78	3.22	0.07	3.33	0.8	4.07	0.95
Japan	4.45	2.46	0.14	2.97	0.63	2.98	0.74
Ecuador	3.21	-	-	2.80	0.30	3.23	0.27
South Korea	2.76	2.49	0.42	3.01	0.86	3.17	0.91
Philippines	2.23	-	-	3.03	0.77	4.65	0.93
Thailand	2.16	-	-	2.78	0.79	4.34	1.00
Turkey	1.72	3.04	0.33	4.36	0.88	5.44	0.90
Britain	1.41	-	-	2.74	0.57	2.48	0.61
Australia	1.25	-	-	2.58	0.72	3.29	0.89
Bangladesh	1.11	2.39	0.50	4.22	0.61	3.66	0.89
Canada	1.02	2.52	0.51	3.30	0.83	3.18	0.85
Mexico	1.02	-	-	3.58	0.71	4.00	0.89
New Zealand	0.83	-	-	3.55	0.35	3.74	0.33
Greece	0.76	2.39	0.03	2.95	0.77	3.84	0.87
Faroe Islands	0.74	-	-	2.55	0.02	5.07	0.02

Average and Proportion values < 2 are represented by “-“ and values > 4 represent extremely dissimilar climates from present.

strategies effectively—protecting current investments and identifying potential opportunities for growth.

This analysis relies on the comparison of climatic environments within a species' native range. However, the existence, or persistence, of wild populations of aquaculture species does not guarantee viable aquaculture production of the same species, as these can exist outside the optimal growth conditions for profitable farming operations. Though not included in this analysis, the addition of introduced ranges based on cultivation that presumably share an environmental niche with the native range of the species, would expand dissimilarity and exposure estimations. Of the species farmed outside the range, we find that 18 species classified as human introduced in the World Register of Introduced Marine Species (WRiMS) are reported of significant mariculture value in the FAO database (Table S3) across 27 countries; that is 43 combinations of species and country. Future research could examine how these species, already being farmed outside their native range, and other farmed species not yet introduced, might find suitable farming conditions outside their native range under future climate conditions. Such work would need to develop new "introduced for mariculture range" maps for these species-country combinations because currently available maps are either for their native range only, or potential range globally. However, there is increasing reluctance to introduce non-native species due to concerns about them escaping and introducing alien pathogens and/or genetic material into the local ecosystem[73,74].

In the Northern Hemisphere, especially the Arctic, climate dissimilarity may not necessarily negatively impact marine aquaculture as increasing temperatures and species movement will increase the number of species available for cultivation in these regions. Increased temperatures may increase growth rates and productivity of currently farmed species. Thus, dissimilarity alone cannot directly identify areas that stand to benefit, in terms of marine aquaculture production, from climate change. However, it can be inferred that the same level of dissimilarity at high latitudes is more likely to be associated with inheritance of productive conditions than at equatorial regions—which may suffer as species currently live at the edge of their temperature thresholds. The feasibility analyses required to initiate the relocation and/or establishment of aquaculture will need to include socio-economic factors beyond the scope of the results presented here but can utilize the distribution of low climate dissimilarity as a starting point for candidate site selection. Additionally, the directionality of change as revealed by climate analogs, though not within the scope of this analysis, may inform the prioritization of development and mitigation efforts as EEZ that may acquire climates associated with highly productive aquaculture in the present are identified.

Conclusion

The geographic distribution of climate change effects on marine aquaculture is not uniform. Some areas are more likely to be negatively or positively exposed. This analysis identifies high-priority regions for adaptation, development, and mitigation measures, applying a novel approach to quantifying regional vulnerability of marine aquaculture to climate change. Evaluation of global climate dissimilarity illustrates, once again, the value of the Paris Agreement in limiting deleterious effects related to climate change and major disruptions to key industries, in this case, marine aquaculture.

Methods

Marine aquaculture species

We identified 327 marine aquaculture species, categorized into six taxonomic groups consisting of 23 algae, 35 crustaceans, 3 echinoderms, 164 finfish, 101 molluscs, and 1 tunicate (Table 1). All species were treated equally in all analyses. This list of species was compiled from the Food and Agriculture Organization (FAO) aquaculture database[31], the Sea Around Us project aquaculture database[75], and various literature sources[38,76–84]. This list encompasses species farmed in the marine environment, open or semi-open marine aquaculture systems such as in net pens, trays, trestles, and long lines for

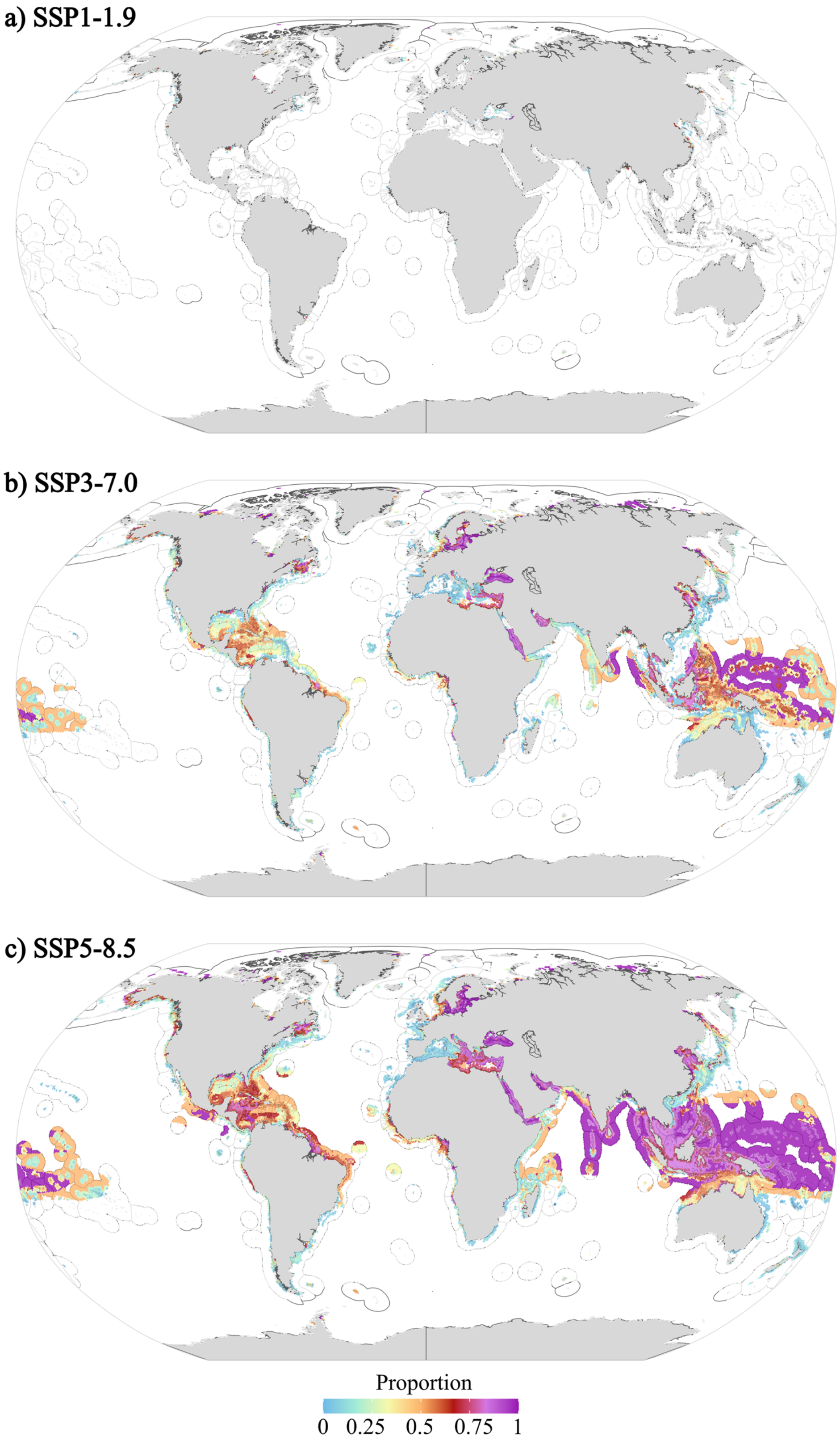

Fig. 5 | The proportion of each EEZ's species exposed to climate dissimilarity per cell of all marine aquaculture species. Species with a mean climate dissimilarity >2 are considered exposed and are presented for the three climate change scenarios considered: SSP1-1.9 (**a**), SSP3-7.0 (**b**), and SSP5-8.5 (**c**). In total, 265 EEZ are included, with colored areas composed of equal-area hexagonal cells (approximately 50 km cell spacing) that aggregate the model output.

commercial use. Marine aquaculture value and production data per country were retrieved from the FAO database[31].

Species' range maps

Range maps for 247 of the 327 species (8 algae, 21 crustaceans, 2 echinoderms, 147 finfish, 68 molluscs, and 1 tunicate) were obtained from AquaMaps, a platform that models global ranges of species[85]. For the remaining 80 species (15 algae, 14 crustaceans, 1 echinoderm, 17 finfish, and 33 molluscs), range maps were generated manually by integrating information on species' distribution obtained from FishBase[86], SeaLifeBase[87], and AlgaeBase[88] and published literature[89]. Based on these records, along with species' latitudinal limits, we created polygon shapefiles encompassing the

Fig. 6 | A scatterplot of the mean climate dissimilarity and log-transformed 2021 aquaculture value (US dollars) for each country with current aquaculture under three climate change scenarios: SSP1-1.9, SSP3-7.0, and SSP5-8.5. The size of the points represented the proportion of species impacted and the color represents the taxonomic group. The top 10 EEZ in SSP1-1.9 (**a**) and the top 20 EEZ in SSP3-7.0 (**b**) and SSP5-8.5 (**c**) were labeled based on equal weighting of dissimilarity and aquaculture value are shown to identify EEZ with high production value and/or high projected dissimilarity. All other EEZ with dissimilarity ≥2 were plotted without labels. A diagram assigning the plot quadrants to proposed routes to resilience is placed in the top right. The quadrants are defined according to four distinct strategies for aquaculture in a given EEZ in the face of climate change: Develop—those with low value and low dissimilarity, Optimize—those with high value and low dissimilarity, Mitigate—those with high value and high dissimilarity, and Adapt—those with low value and high dissimilarity.

coastal distribution of each species in QGIS[90]. Occurrence records from the Global Biodiversity Information Facility (GBIF)[91] and the Ocean Biodiversity Information System (OBIS)[92] were compared to the shapefiles to ensure agreement across data sources. The shapefiles for each species (either AquaMaps-derived or manually constructed) were rasterized, before being converted to coastal range maps. These range maps represent a species predicted range in the past and may not account for shifts due to climate change or extirpations for any reason. A species is never present everywhere in its range all the time due to local habitat suitability, therefore the range maps are an estimation of the potential spatial area a species may currently inhabit. The range maps and subsequent dissimilarity projections do not include areas of cultivation for a given species outside its native range.

Climate data

The Bio-ORACLE computational pipeline[93] was used to generate climate layers for the ocean's surface level, at a global scale and 0.25° resolution, per year, for the current baseline conditions (period 2010 to 2020) and the projected conditions of future change (period 2090 to 2100). Three Shared Socioeconomic Pathway (SSP) scenarios of future change were analyzed: (1) SSP1-1.9, the "sustainability" scenario following the Paris Agreement expectations of reduced carbon emissions, (2) SSP3-7.0, the "regional rivalry" scenario which represents medium-to-high carbon emissions, and (3) SSP5-8.5, the "fossil fuel development" scenario of higher carbon emissions and challenges to mitigation[23,24,94]. The variables considered relevant to define the species' "climatology" were sea temperature, dissolved oxygen, primary productivity of phytoplankton, salinity, nitrogen, and phosphorous. In the case of crustaceans and fish which are fed by the farmer, variables associated with nutrition, i.e., phytoplankton, nitrate and phosphorous, were excluded. The data used for current conditions were obtained from Copernicus Marine Service, whereas the data used for future climate scenarios were generated from the ensemble (average) of several Earth System Models[93] (ACCESS-ESM1-5, CanESM5, CESM2-WACCM, CNRM-ESM2-1, GFDL-ESM4, GISS-E2-1-G, IPSL-CM6A-LR, MIROC-ES2L, MPI-ESM1-2-LR, MRI-ESM2-0, UKESM1-0-LL) provided by the 6th version of the Coupled Model Intercomparison Project (CMIP).

Dissimilarity analysis

Climate dissimilarity quantifies differences between two distinct climates. It expands upon the multivariate Standardized Euclidean Distance (SED), which normalizes climate variables based on the local intra-annual climate variability. It adapts the SED to Mahalanobis distance and interprets climate distances as percentiles of the chi distribution[26,27]. The Mahalanobis distance, a measure of the distance between two points in a multivariate space, ensures that variables are scaled relative to the intra-annual climate variability and eliminates variance inflation caused by correlations. The probability distribution of the Mahalanobis distance gives rise to "chi percentiles using the terminology of univariate z-scores, that is, 1σ, 2σ, and 3σ (sigma) to describe the 68th, 95th, and 99.7th normal percentiles, respectively" also known as the sigma dissimilarity metric[27]. Sigma dissimilarity (σ) is scored from 0 to ~8.3 with values greater than 0 suggesting conditions different from those present at any point within the current species range. The chi distribution-based statistical interpretation is necessary as it considers the effect of dimensionality, allowing for meaningful comparisons between analyses using differing numbers of input variables[27,95]. This index considers various climatic variables to identify similar climates across space and time (i.e., analogous), as well as species and regions that are vulnerable to climate change[28].

To assess the exposure of marine aquaculture species and regions to climate change, we estimated climate dissimilarity between projected conditions of each 0.25° (approximately 5.5 km × 5.5 km at the equator) ocean pixel (decade 2090–2100) and their closest analog of current conditions (decade 2010–2020). Sigma dissimilarity was determined by species, using the above-listed environmental variables. To evaluate the global exposure of marine aquaculture to climate change, we first determined the mean sigma dissimilarity (with values greater than 2, the threshold associated with moderate climate novelty established by Mahony et al.,[27], signifying notable change) aggregated per equal area hexagonal cell for each species, aggregated by taxonomic group, within its native range as well as for all taxonomic groups combined. Next, we determined the proportion of species exposed to climate dissimilarity (experiencing sigma >2) within each EEZ for each taxonomic group and for all taxonomic groups combined. We then determined the proportion of species exposed per hexagon relative to the global total number of marine aquaculture species (i.e., 327). Hexagons corresponded to a cell area of approximately 2600 km^2 and a cell spacing of approximately 50 km, a size selected to provide an effective visual summary of regional information at a sub-EEZ scale.

To visualize the countries with existing marine aquaculture most exposed relative to their 2021 aquaculture production value in US$[31], we plotted the marine aquaculture value against mean sigma dissimilarity. Marine aquaculture value was log-transformed to reduce bias caused by a few countries with disproportionately high values. The plot was divided into quadrants, categorizing countries into four distinct strategies: Develop—those with low value and low dissimilarity, Optimize—those with high value and low dissimilarity, Mitigate—those with high value and high dissimilarity, and Adapt—those with low value and high dissimilarity. Quadrant division points were chosen based on meaningful thresholds to facilitate grouping EEZ by production and exposure. The x-axis, denoting mean dissimilarity was divided at a value of 4, the threshold for extreme dissimilarity established in Mahony et al.[27]. The y-axis, representing log-transformed marine aquaculture value, was divided at 6, the equivalent of 1 million US$. We applied an extremity weighting (W) to highlight the countries at the leading edge in terms of high marine aquaculture value, high climate dissimilarity, or both, as described by Eq. (1):

$$W_i = z(\log_{10}^2(Value_i)) + z(\sigma_i) \qquad (1)$$

where $z(.)$ is the standardization of a variable, $Value_i$ is the 2021 value in US $ derived from marine aquaculture for a given EEZ, and σ_i is the average sigma dissimilarity for that same EEZ.

Data availability

Climate data were retrieved from the Copernicus Marine Service at [http://resources.marine.copernicus.eu/products] and the Coupled Model Intercomparison Project (Phase 6) at [https://esgf-node.llnl.gov/projects/cmip6/] in May 2023. Species' range maps were retrieved from AquaMaps at [https://www.aquamaps.org] in May 2023.

Code availability

Our manually-derived range maps are available on figshare[89] and our code on GitHub (https://github.com/jorgeassis/climateAnalogs).

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Author contributions

A.L.M., G.G.H.: Conceptualization, Methodology, Interpretive Analysis, Investigation, Data Curation, Writing—Original Draft, Writing—Review & Editing, and Visualization. M.J.C.: Conceptualization, Investigation, Writing—Review & Editing, and Funding Acquisition. J.A.: Conceptualization, Formal Analysis, Writing—Review & Editing, and Funding Acquisition. A.L.M. and G.G.H. contributed equally to this manuscript.

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Correspondence and requests for materials should be addressed to Amy Leigh Mackintosh.