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Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture

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Fisheries and aquaculture make a crucial contribution to global food security, nutrition and livelihoods. However, the UN Sustainable Development Goals separate marine and terrestrial food production sectors and ecosystems. To sustainably meet increasing global demands for fish, the interlinkages among goals within and across fisheries, aquaculture and agriculture sectors must be recognized and addressed along with their changing nature. Here, we assess and highlight development challenges for fisheries-dependent countries based on analyses of interactions and trade-offs between goals focusing on food, biodiversity and climate change. We demonstrate that some countries are likely to face double jeopardies in both fisheries and agriculture sectors under climate change. The strategies to mitigate these risks will be context-dependent, and will need to directly address the trade-offs among Sustainable Development Goals, such as halting biodiversity loss and reducing poverty. Countries with low adaptive capacity but increasing demand for food require greater support and capacity building to transition towards reconciling trade-offs. Necessary actions are context-dependent and include effective governance, improved management and conservation, maximizing societal and environmental benefits from trade, increased equitability of distribution and innovation in food production, including continued development of low input and low impact aquaculture.

Minimizing biodiversity loss and achieving sustainable food production are two of the toughest societal challenges highlighted in the UN Sustainable Development Goals (SDGs) given many inevitable trade-offs on the environment–human axes of the SDGs[1]. Critically, there are different types of interactions between SDGs and the marine and terrestrial ecological processes and food production systems on which they rely. First, production from fishing, farming and aquaculture all support poverty alleviation (SDG1, no poverty; SDG10, reduced inequalities) by helping poorer people, especially those dwelling on coasts in sub-tropical and tropical regions, to maintain their food supply and income in variable environments[2,3]. Second, fish from wild capture fisheries and aquaculture make a crucial contribution to both global food production and overall nutrition (SDG2, zero hunger; SDG3, good health and well-being), providing 3 billion people with almost 20% of their mean per capita intake of animal protein[4] and providing essential micronutrients in otherwise deficient diets[4,5]. Third, increases in fish production to meet the food and livelihood demands of the growing human population, projected to reach 9.7 billion by 2050[6], will increase pressure on marine and terrestrial ecosystems unless there are significant reductions in the environmental impact of many existing production systems (SDG12, responsible production and consumption; SDG14, life below water; SDG15, life on land). Last, all food production systems are both impacted by, and produce feedbacks to, climate change (SDG13, climate action) and opportunities for building climate-resilience may exist across sectors but may be masked within single-sector assessments.

Interactions between aquatic and terrestrial food production sectors, particularly through shared resources and cross-ecosystem impacts[7–10], are changing[11]. Although fish production historically was dominated by wild capture marine fisheries, as of 2014 humans consume more cultured fish than wild fish[4]. Wild capture fishmeal and oil are used to feed farmed fish as well as livestock[12], but this has been proportionally decreasing due in part to their rising prices, instability of supply, shifts towards direct consumption, improved feed technology and sustainability concerns of using wild-caught

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fish. Consequently, an increasing proportion of cereal and soya production is being channelled to fish aquaculture as feed[13,14], affecting land-based human food production. Changes in production and use of feed will affect types and volumes of crops, fish and livestock available; prices; equitability of access; and the balance of biodiversity impacts between sea and land. To assess the sustainability of food production, it is crucial to understand how such shifting sea–land linkages will affect resilience[13] to climate variation and change, the new threats and opportunities that arise for the food system, opportunities for livelihoods in fishing, aquaculture and farming, and the associated biodiversity impacts of production.

Here, we investigate and highlight the complex interplay between fisheries and other sectors under climate change and their potential implications for biodiversity conservation, livelihoods and food security. We show how an integrative land–sea and social–ecological approach is essential to reveal some of the major challenges for fisheries and other sectors that will have to be understood and managed to meet the SDGs. We emphasize how alternative regional and national futures, and thus progress towards meeting SDGs, will depend on developments in aquaculture and farming, differences in adaptive capacity, climate change on land and sea, and changing patterns of wealth, demand and trade.

Fish demand and production

The growing human population, coupled with a burgeoning middle class[15] that can afford to consume more animal protein[16,17], is contributing to an increased consumption of fish and aquatic invertebrates (herein called fish). Mean global per capita fish production from fisheries and aquaculture has more than tripled in the past half century, outpacing growth in all other livestock sectors, including chicken, pork and beef, as well as contributing the most to food supply in terms of production since 1960[18,19]. Total wild fish catches have fluctuated around 90 million tonnes annually since 2000. The continued growth of global fish production is driven by increasing freshwater and marine aquaculture production, which has grown to 74 million tonnes (2014) and now provides half the fish eaten by people globally[4]. However, just 25 countries supply 96%, by weight, of all farmed fish[4]. Therefore, despite some growth of aquaculture production almost everywhere (except the Oceania region[4]), for many countries a greater proportion of their fish production is still reliant on marine wild capture fisheries (Fig. 1a and Supplementary Information).

There is substantial variation in per capita fish supply across countries (Fig. 1b). Mapping the relative change in per capita domestic fish production (marine and freshwater aquaculture and wild capture fisheries plus imports less exports per person) from 1980–4 to 2010–4 reveals pronounced contrasts with the relative change in human population over the same time period (Fig. 1b). For example, China is keeping pace with fast human population growth rates through a combination of aquaculture development and marine capture fisheries. The footprint of Chinese fishing vessels extends across the territorial seas of 93 other countries around the world[20]. In contrast, Chile's falling per capita fish supply is driven by declining stocks[21] and large exports (six times more than their imports) widely used to supply global markets for fishmeal and oil[22,23]. While Chile has developed a significant aquaculture industry, other countries with falling per capita supply, especially in parts of Africa and the Middle East, have not (Fig. 1).

Sustainability of fisheries

Fishery management systems seek to meet objectives for ecological, social and economic sustainability, but improving outcomes for any one axis of sustainability may come at a cost to another[24,25] and there are fundamental ecological limits on social and economic benefits.

Assessments of the state of targeted fish stocks provide the main benchmark for the performance of fisheries management.

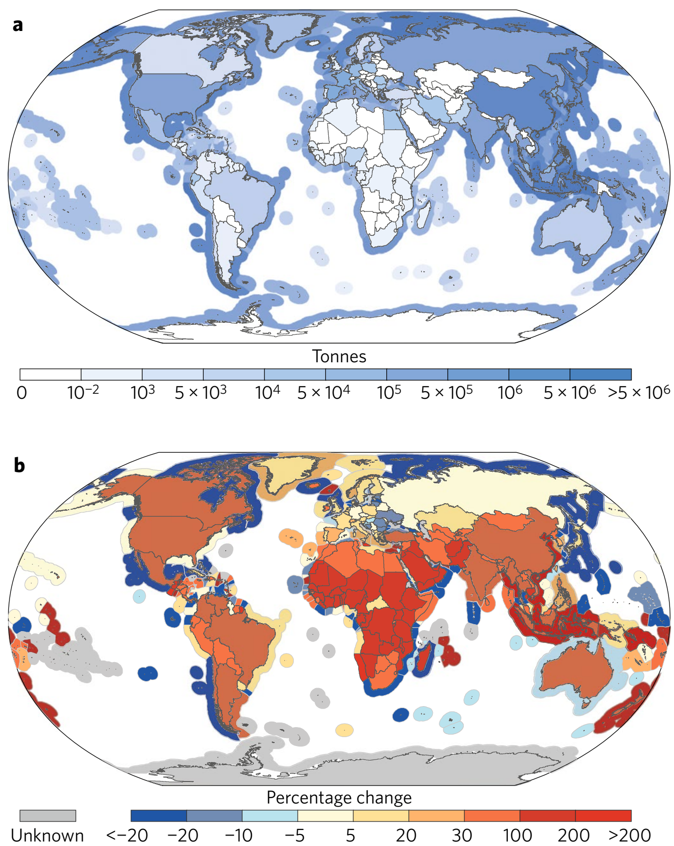

Fig. 1 | Country-level trends in per capita fish supply, human population growth, and access to wild capture fisheries versus aquaculture. **a**, Geographical variation in current (2010–2014) fish production from marine wild capture fisheries (shading in marine exclusive economic zones; EEZ) compared with aquaculture and inland fisheries (shading on land). Fisheries production and trade data from Food and Agriculture Organization's (FAO) data supplemented by regional datasets[114]. A compilation of global landings data was mapped by intersecting statistical reporting areas with information on fisheries access and marine species distributions. **b**, Map of recent percentage changes (2010s relative to 1980s) in the human population (shading on land) compared to total per capita fish supply (shading in marine EEZ).

Globally, 31.4% of fish stocks assessed are classified as overfished by the Food and Agriculture Organisation of the United Nations (FAO)[4] (based on a mix of quantitative assessments and national and regional expert judgement; violet shading Fig. 2a). The proportion of stocks overfished varies geographically from <20% in the northeast and eastern central Pacific and eastern Indian Ocean, to >40% in the southeast Pacific, southwest Atlantic and across the eastern and western central Atlantic and 59% in the Mediterranean and Black Sea[4] (Fig. 2a). An alternative quantitative analysis of stock assessment data generally implied higher levels of overfishing than the FAO approach in those regions where comparisons were possible[26] due to greater coverage of smaller stocks. Large stocks, which account for a greater proportion of global fisheries landings and are often targeted by larger vessels and fewer fishers per unit of catch are, in general, the focus of more rigorous management and likely to have better status than smaller stocks[27,28].

The geographical, taxonomic and temporal scope of fish stock assessments is typically narrow in relation to the ubiquity of fisheries and their impacts. While stocks collectively supporting the majority of catch are routinely assessed in some exclusive economic zones (EEZ, for example, United States, Australia, New Zealand,

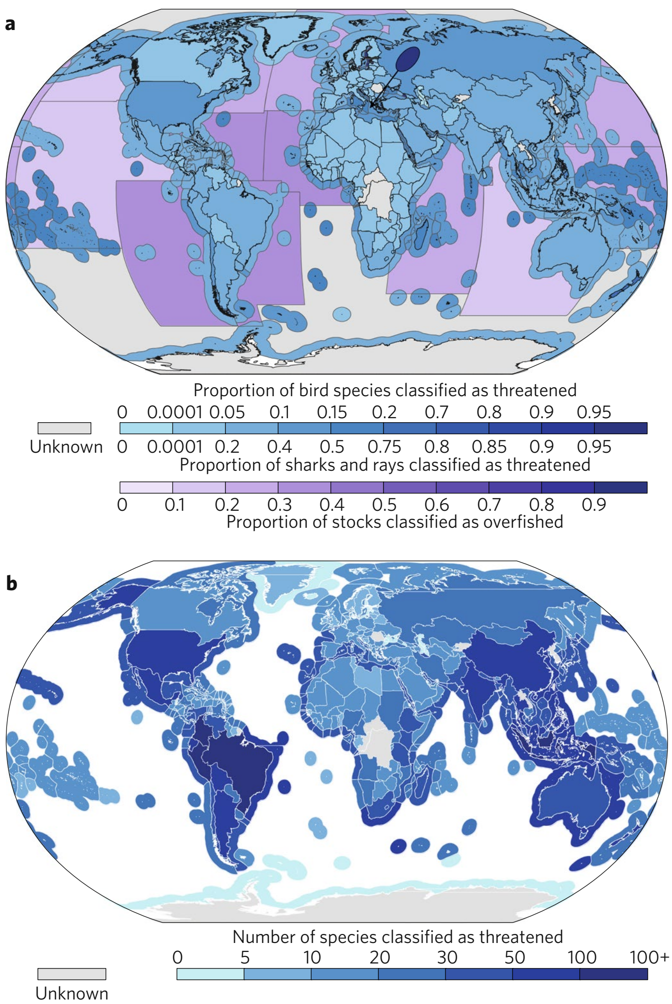

Fig. 2 | Fisheries and biodiversity threat status on land and sea. a, The proportion of fish stocks overfished in each ocean basin (FAO areas, violet) combined with the proportion of marine shark and ray (blue shading in the sea for each EEZ) and terrestrial bird species (blue shading on land by country) that are threatened. The dark violet bubble ellipse indicates the proportion of overfished stocks (0.59) in the Mediterranean and Black Sea FAO area (see Supplementary Information). **b**, The total number of threatened shark and ray (coloured in EEZ) and bird (coloured on land) species by country.

South Africa and parts of Europe; see Supplementary Information) assessments elsewhere may be sporadic, not to be linked to systematic management or strong fisheries governance, and only cover a small proportion of the catch in terms of weight and species diversity[29,30]. There are many smaller stocks that remain unassessed, and these often support inland[31] and coastal livelihoods and food security in regions where fisheries dependency is high and assessments are scarce[29,32]. For small-scale fisheries, including many tropical coral reef[33] and invertebrate[32] fisheries that are critical for nutrition, income and employment[34,35], few stock assessments are conducted and almost none of the catch comes from assessed stocks[36].

Recent advances in data-limited catch-based models[27,37] and their combination into superensemble models[38] are enabling inferences to be made about many more data-poor and smaller unassessed stocks[39]. While superensemble estimates of stock status (33% overfished) are globally comparable to the FAO and quantitative stock assessment models they also provide more precise information on stock status, instead of the broad categories used by FAO. They offer a powerful synthetic approach for combining catch data with additional information such as life histories and stock size and could be developed to include alternative data types. At a very localized scale the monitoring of catches is highly challenging when these fisheries take a broad range of species and land them in many locations[40]. In this case, other sources of abundance data may be available to assess fishing impacts, such as extensive underwater visual census data for reef and shallow-water species[41,42] and occasionally trawl surveys[43,44]. Additionally, for vulnerable, non-target or data-limited fish populations, International Union for the Conservation of Nature's (IUCN) Red List assessments have shown compatibility with stock assessments and thus their potential for fisheries sustainability as well as wider biodiversity reporting[45,46].

Biodiversity status and food production

On land, the main human pressure leading to biodiversity and ecosystem change is predominantly land-use change linked to agriculture[47], while in the sea, it is predominantly fisheries exploitation and, close to coasts, habitat modification, loss and pollution[48]. One of the most comprehensive databases available for assessing global biodiversity threat is the IUCN Red List[49]. The IUCN conduct assessments of extinction risk for different populations and species. The most taxonomically complete marine global database is that for the status of sharks, rays and chimaeras (class Chondrichthyes; hereafter sharks and rays)[50]. Furthermore, many of these fishes are among the most sensitive to fishing mortality and, unlike other marine teleost fishes, the status of all known species has been assessed in relation to IUCN Red List criteria. For sharks and rays listed as threatened (sum of species classified as Critically Endangered, Endangered or Vulnerable), the main threatening process was exploitation ('biological resource use') in 99% of cases[49]. As an illustrative terrestrial comparison, birds (class Aves) are regarded as the most comprehensively assessed terrestrial class of organisms on the Red List[51]. Land-use change is one of the main drivers of change in bird biodiversity, with agriculture being identified as the main threat to 82% of listed species (excluding seabirds)[49]. Consequently, their status provides a suitable broad-scale indicator of the impacts of agriculture on biodiversity[52], although responses of a given species in specific habitats to a given change in agriculture are clearly more nuanced[53,54].

For the Red List indicators, both on land and in the sea, the number of threatened species (N_T) is greatest in the tropics, where there are more species (Fig. 2b). From a conservation and management perspective, high absolute number of threatened species is an important issue because species are often dealt with individually in management plans, increasing institutional, monitoring and political difficulties and costs. However, when the numbers of threatened species are expressed as a proportion of species richness (P_T), the effects of human pressures on biodiversity in many mid- and high-latitude nations are revealed to be as profound as those characteristically highlighted in the tropics (Fig. 2a; for both Red List indicators). P_T provides a complementary index for comparing the consequences of pressures on the environment when species richness per unit area of many groups varies by an order of magnitude or more across latitudes. For example, in some lower latitude areas such as Australia, many species are threatened (73) but the proportion of threatened species (0.22) is relatively low, perhaps reflecting the small footprint and low intensity of bottom fishing[55], which is likely to be one of the main drivers of status.

Biodiversity, human development, food system dependency

Many links between biodiversity threat status, human development, fisheries and aquaculture dependency and agricultural dependency are driven by processes and decisions at national scales. Although biodiversity threat is best assessed over the spatial distribution

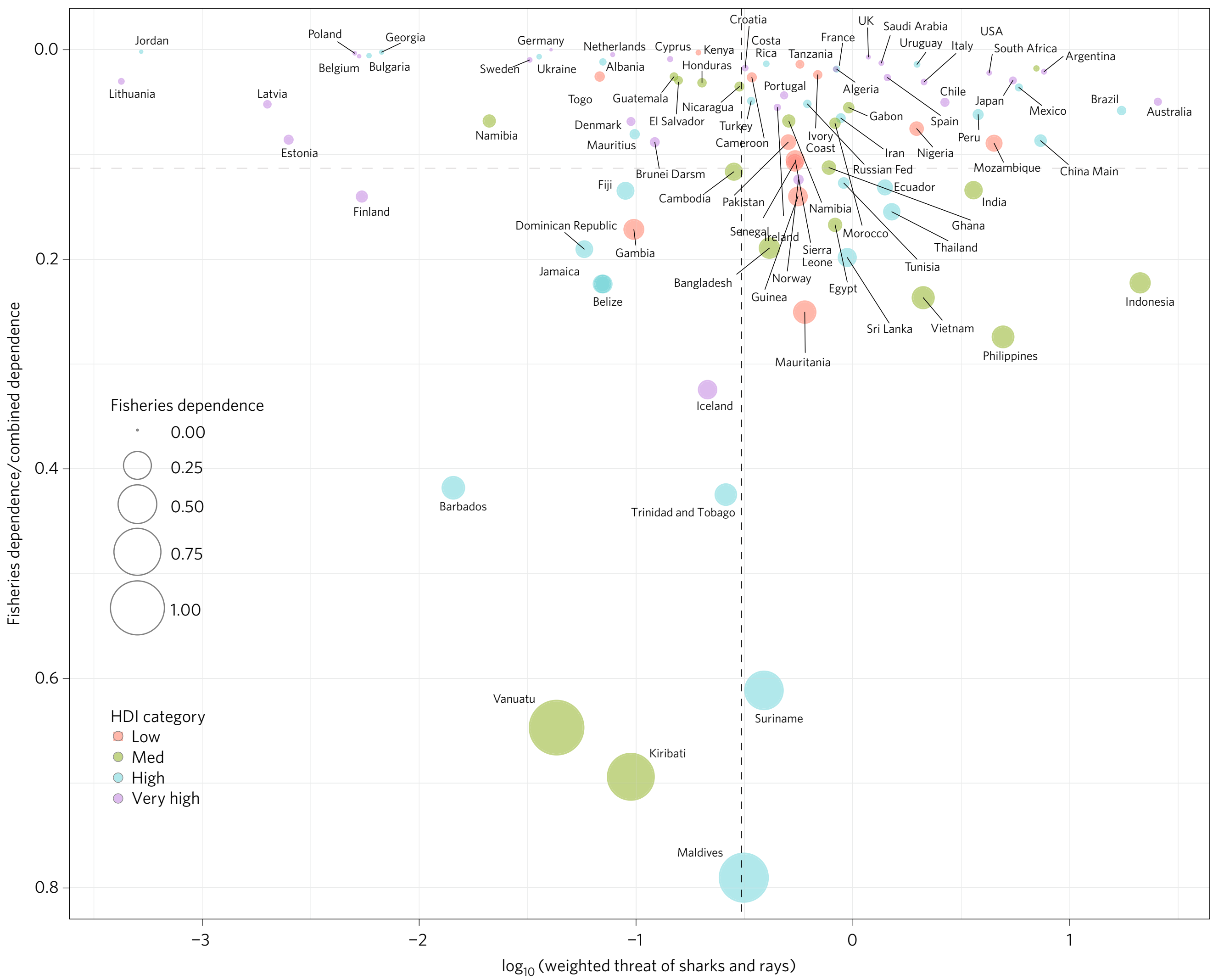

Fig. 3 | Marine biodiversity threat and adaptive capacity in fisheries-dependent countries. Country-level dependence on fisheries relative to combined dependence on fisheries and agriculture and the weighted threat of marine sharks and rays for each country. The dependence indices were calculated using publicly available online data from FAO, the World Bank and a recent compilation of employment data[115]. Colours represent categories of the human development index (HDI). Only countries where dependence indices were available are shown. Dashed lines indicate average values of relative threat and fisheries dependence across all countries included in the analysis.

of species[56], country-level indices help to evaluate how progress towards global biodiversity targets is influenced by national conservation actions and human development[57]. Weighted threat (W_T) is one such index, and is calculated as the sum of the fractions of threatened species' ranges within each country[57].

Human development at national scales can be measured in many ways which may focus on well-being, equality and adaptive capacity[58]. We adopt the human development index (HDI), which is a composite index of life expectancy, education and per capita income[59] and is closely correlated with adaptive capacity and other measures of development (Supplementary Information). For dependency on different food systems (fisheries or agriculture) we adopted an index that measures the contribution of fisheries or agriculture to national employment, the economy and food provision (Supplementary Information).

Countries with the highest weighted biodiversity threats for shark and ray species span the full range of HDI categories (Fig. 3), the top-three of which are Australia (very high HDI), Indonesia (medium HDI) and Brazil (high HDI). Some low (Mauritania, Gambia and Guinea) and medium (Kiribati, Vanuatu, Philippines, Vietnam, Indonesia, Bangladesh, Egypt, India and Cambodia) HDI countries have higher than average dependence on fisheries and relatively high weighted threat values for sharks and rays, exemplifying trade-offs between SDGs, albeit based on our restricted taxonomic and country-level comparison (Fig. 3). For these and other countries (for example, China[60]), attaining zero hunger (SDG2) and no poverty (SDG1) will be constrained by efforts to protect life below water (SDG14), unless dependence on fish and fish products changes in the future or they can be produced in less-impactful ways. Where geographic and taxonomic coverage permits, more detailed regional pressure–state–driver–response analysis could be carried out to establish how threat status relates to current and future land/sea-use, particularly in regions where there is monitoring of marine and terrestrial ecosystems and changes in human drivers[61].

Climate variability and change

Understanding the full suite of climate impacts on food systems is complex due to the multitude of pathways, management systems, substitutability, dependence and cross-sectoral links. Reduced domestic production in one sector may increase pressure to obtain food from other sources, so it is critical to understand climate effects on fisheries in the context of effects on other sources of food production and trade.

Ecosystems and the food production systems reliant upon them are dynamic and influenced by environmental variability and longer-term change[62–64]. Fisher and farmer incomes, food supply and prices are less stable when yield variability over time is high. Wild fisheries catches, particularly for small-bodied pelagic species abundant in upwelling ecosystems, show large inter-annual and inter-decadal fluctuations with climate[10,11]. For example, differences between the lowest and highest annual catches of Peruvian anchovy have exceeded 14 million tonnes since 1950 (FAO, FishStatJ), around 15% of the global total annual yield of wild capture fisheries in recent years. Yield variability in this and other fisheries has implications for incomes, employment, food supply, and dependent industries such as aquaculture and agriculture[12]. Notwithstanding these challenges, fisheries that have persisted have adapted to significant and unpredictable changes in productivity, and may build adaptive capacity through diversification of fishing gears, targeted species, adaptive management and associated supply chains[65,66]. In West Africa, for instance, strategies to cope with sudden shifts in fisheries are wider-reaching and have included turning to seafood imports[67] or terrestrial food production, including farming and bush-meat hunting on land[68].

Fisheries and agriculture interact with climate change and biodiversity, leading to profound changes in ecosystem structure and function. Shifts in the size-structure of marine or terrestrial communities are often driven by fishing and agriculture making them more sensitive to climate variability and longer-term change[69,70] as well as having consequences for nutrient recycling and hence primary productivity[71–73]. For any particular marine or terrestrial species, impacts of increased temperature depend on optimal temperatures for growth and reproduction, affecting habitat suitability. Species redistributions, tightly linked to changes in habitat suitability and climate velocities, are likely to impact ecosystems and food production in ways that are not yet fully understood[74]. Large changes in catch composition[75] were linked to warming from 1982 to 2006 that was especially rapid in the sub-Arctic Gyre, European and East Asian Seas, which warmed at 2–4 times the global rate[76]. On land, global wheat yields were estimated to have decreased by 5.5% on average due to warming between 1980 and 2008. But country-specific losses due to climate varied greatly around this estimate; yield reductions in Russia were estimated at 15%, compared with no warming effect on wheat production in the United States[77]. Spatial changes to the suitability of livestock systems are also predicted to arise from increases in metabolic demands imposed on domesticated animals from heat stress — particularly in low-latitude grazing systems pressured further by forage and water scarcity[78]. While variability around future climate trends is a fundamental feature of climate projections, current climate models used for deriving ecological responses are not capable of accurately predicting climate variability on sub-decadal scales[79]. Thus, we are constrained to providing projections of effects on potential fish and crop production after several decades (for example, typically 2050), when the anthropogenic climate change signal is expected to emerge from the background variability[80–83].

Global climate change projections are used for projecting the future evolution of agricultural crops[84] and marine fisheries[81–83,85–87] sectors, but these are less developed for livestock[88] or aquaculture[22]. Here, we compare recent climate change projections across marine fisheries and agriculture sectors using simulation outputs from the Inter-Sectoral Model Intercomparison Project (https://www.isimip.org/, Supplementary Information). Although crop agriculture is often claimed to be the sector most affected by climate change[84], projected changes in marine fisheries production may be just as large, according to multi-model ensemble results compiled for both sectors (Fig. 4, Supplementary Fig. 1).

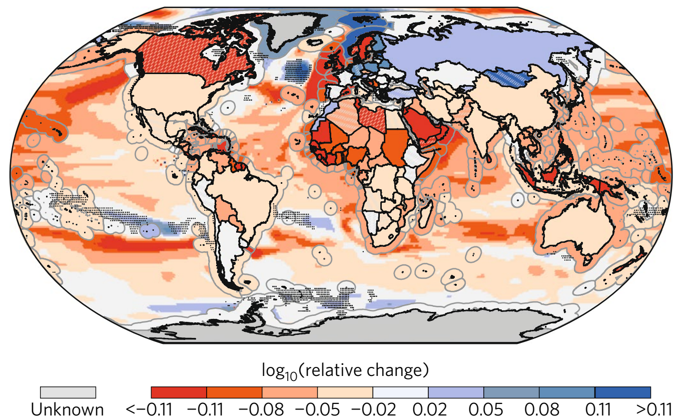

Fig. 4 | Multi-model ensemble climate change projections for potential production of marine fisheries and agriculture sectors. Projected relative changes in potential crop (maize, wheat, rice and soy combined) and fish production from Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) and Coupled Model Intercomparison Project Phase 5 (CMIP5) ensemble outputs[92,116]. Crops are from the published agriculture model intercomparison project (AgMIP) for model ensemble outputs based on seven crop models and seven general circulation models[84]. Predicted mean relative changes for total marine fish consumer biomass from the fisheries and marine model intercomparison project (FISH-MIP) model ensemble consisting of four marine ecosystem models[82,85,87,95] forced by two Earth system models without fishing impacts. Stippling indicates model disagreement for over 50% of the models. Results are shown for RCP6.0 scenario (2050 relative to 2010) but see Supplementary Fig. 1 for comparison with other RCPs.

The projections across the series of representative concentration pathway (RCP) scenarios for future greenhouse gases and multi-model ensembles (Supplementary Information) capture some aspects of uncertainty about future climate and climate impacts on fisheries and agriculture[89,90]. It is important to bear in mind that, for any assumed RCP, the general circulation and ecological models (Supplementary Fig. 2) do not represent many smaller-scale and transient processes that can be important drivers of production at regional, national and shelf-sea scales[91] (Supplementary Fig. 3). Further, model projections are all based on simple assumptions about future farming and fishing strategies, as well as national access to resources, that may not hold. For a given RCP, more confidence can likely be placed in agriculture and fish production model projections when there are high levels of model agreement (Fig. 4). Taking these inherent uncertainties into account, the majority of countries may risk exposure to the double jeopardy of projected declines in both sectors across all RCP scenarios (Supplementary Fig. 1).

The RCP6.0 scenario model ensemble projections reveal decreases in both marine and terrestrial production affect 87 out of 119 of coastal countries that vary widely in adaptive capacity, as measured by the HDI, and also in their relative and combined dependency on fisheries and agriculture (Fig. 5). Countries facing the greatest projected marine sector impacts include Denmark, Ireland and Latvia where overall dependence on fisheries is relatively low, adaptive capacity is very high, but where conserving biodiversity remains a challenge. Most of the projected increases in agricultural production are in Europe (12 of the 17 coastal countries with increases), where adaptive capacity is higher and dependence on agriculture and fisheries for food and employment is lower (Fig. 5). In contrast, the greatest projected negative agriculture impacts, in terms of percentage decline in production, are for the island nations of Grenada, Saint Vincent, Bahamas, Barbados, Vanuatu, Mauritius, Sao Tome Principe and Malta. These countries are relatively more

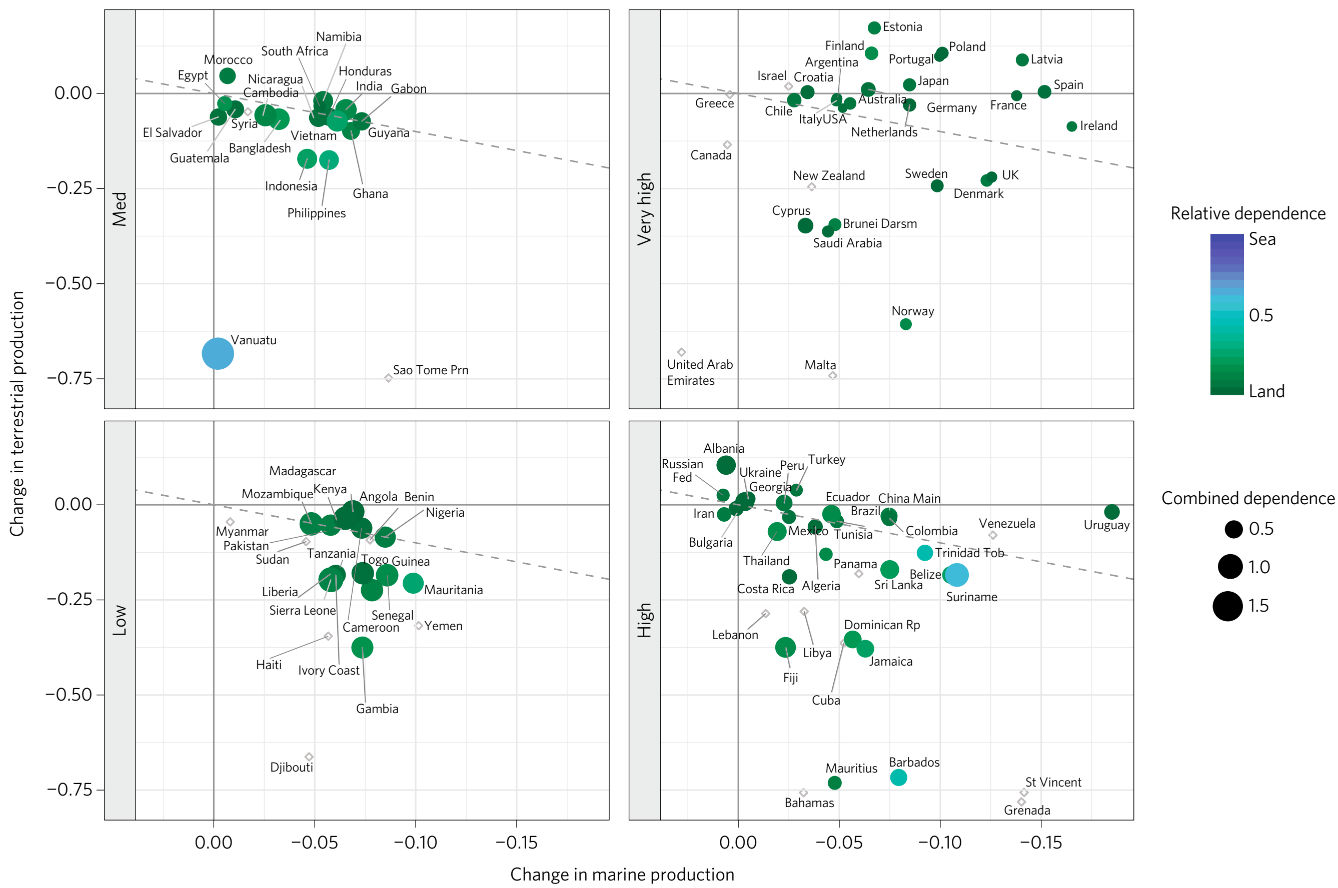

Fig. 5 | Climate change impacts and adaptive capacity by continent across land and sea. The vulnerability of societies to climate change impacts in fisheries and agriculture. Changes in marine and terrestrial production are expressed as $\log_{10}$(projected/baseline) production, where values below zero indicates decreases and above zero are increases. Fisheries and agriculture dependency estimates calculated from employment, economy and food security[83]. Circle size represents total dependency on both sectors and green to blue colour scale reflects the balance between land and sea with turquoise indicative of equal dependence. The dependence indices were calculated using publicly available online data from FAO, the World Bank and a recent compilations of fisheries employment data[115]. Each panel represents the four human development index (HDI) categories (low, medium, high and very high) and open diamonds indicate no data for agricultural and fisheries dependency. See Supplementary Information for more details.

dependent on marine fisheries production but all, except Vanuatu, show projected declines in that sector as well. The identification of countries of coinciding agriculture-fisheries impacts from climate change is the first step towards addressing national or regional vulnerabilities[92]. For countries where projections suggest risk to agriculture and fisheries production is potentially high, risk estimates could be further investigated and refined using downscaled climate projections and ecological models that better capture processes specific to these nations and EEZ.

Climate change impacts leading to similar relative reductions in both fisheries and agricultural production are projected for the high fisheries-dependent and low–medium HDI countries of Nigeria, Cameroon, Ghana and Gabon where food insecurity, fisheries overexploitation and human population growth rates are also high (Fig. 5). Maintaining a diversity of livelihoods will likely remain a commonly deployed solution for coastal communities attempting to secure income and reliable food sources in the context of variable and changing environments. Nonetheless, in these countries, alternatives may be limited, and imports and innovative solutions to increase food production are most likely to be needed[93,94], potentially building on those already in place (for example, Ghana[67]). In sum, this synthesis demonstrates the substantial heterogeneity in climate impacts on food systems and emphasizes the need to better understand the complex and country-specific trade-offs that will be involved in maintaining or achieving food security while minimizing land–sea biodiversity threats and adapting to climate change.

Challenges and solutions

Our synthesis of land–sea and human–environment interactions reveals trade-offs and challenges for countries seeking to meet SDGs. This broader cross-sectoral and ecosystem perspective highlights some fisheries-dependent countries that could face a combination of future reductions in productivity on land and sea, low adaptive capacity and high existing pressures on terrestrial and marine biodiversity; posing significant national and international sustainability challenges. Equally, it highlights some countries (such as Norway, Denmark, Ireland and the UK) that may experience reduced productivity on land and sea but have higher adaptive capacity to deal with these impacts including diversified food systems.

Risks of declines in land–sea food productivity under climate change were apparent across all greenhouse gas concentration scenarios (Supplementary Fig. 1). Although we emphasize the utility of this cross-sectoral climate impact approach, further work is needed to improve the accuracy and uncertainties associated with projections. To improve assessment of national risks, we recommend significant emphasis on developing and/or applying regional physical models (ideally forced by a range of General Circulation Models (GCMs) and RCPs), as well as adopting agricultural and fisheries models that seek to account for drivers of production at national and shelf-sea scales. We further recommend a focus on countries where our analysis suggests there will be large negative impacts on agricultural or fisheries productivity and where dependence and risks to biodiversity are high and where adaptive capacity is low. Interpretation of outputs and development of scenarios should consider future farming, fishing, aquaculture and biodiversity conservation strategies, as well as national access to resources and equitability of distribution.

Further improvements to fisheries management are needed to reduce overfishing, biodiversity loss (SDG14, life under water), and in many cases to meet food, poverty and well-being SDGs. However, even with effective single-species management estimated additional global yields will not be sufficient to meet increasing demand and counter plausible climate change effects on total production[28,95]. Technical barriers currently limit exploitation of sparsely distributed resources (for example, mesopelagic fishes) or the adoption of theoretically desirable fishing patterns without overfishing larger and more vulnerable species (for example, balanced harvesting). Societal and political barriers also curb access to potentially productive resources (for example, krill, because they support Antarctic whale–seabird ecosystems) and social preferences and economic pressures focus fisheries on few species as opposed to balanced or alternative ecosystem harvesting strategies. There is also a mismatch between theoretically optimal fishing strategies that may maximize long-term yields (for example, fishing only when populations exceed threshold abundance[96]) and the capacity of society to accept, adopt and adapt to them. Consequently, we expect that wild seafood will make a vital but decreasing relative contribution to world food supply in the next 30 years as more controlled production systems, especially aquaculture and agriculture and, in the longer term, novel and lower impact methods of feed and food production, become dominant[93,97].

Some developed countries have made significant progress towards sustainable fisheries management but will need to minimize risks that negative impacts are not displaced elsewhere. Reductions in landings associated with meeting objectives to lower exploitation rates can drive higher demands for imports or alternative protein sources. Given strong interdependencies through international trade and fisheries agreements, and the limited management and governance capacities in some developing countries, these demands can have negative environmental and social consequences[98]. Further, benefits derived from exporting fish production may accrue to those who currently hold financial or political power rather than all participants in the supply chain, with adverse social outcomes for small-scale producers and minorities[99]. Better understanding these interdependencies[100], recognizing links between ecological and social sustainability, encouraging responsible sourcing by importers, modifying seafood demand and bolstering wild production through aquaculture may all play a role in helping to ensure that national and regional improvements in fisheries management do not have perverse global outcomes.

Continued sustainable development of aquaculture is needed to meet future demands for fish. Aquaculture production can substitute and complement wild capture production but will rely on effective development and environmental management in countries in need. At present, aquaculture and imports make a minimal contribution to the overall fish production in regions facing the greatest cumulative impacts and population growth rates (for example, countries including Mauritania, Namibia, Angola and Somalia). Faster adoption of existing knowledge and technology in aquaculture could help, but recognizing environmental and logistical limits on the scope to develop freshwater aquaculture in some of these countries. One major concern about the development of aquaculture has been the use of wild stocks to feed farmed fish. The proportion of directly consumed capture fisheries production, including small forage fish, increased from the mid 1990s to 86% in 2012, while the absolute production of fish meal and oil, in part used for aquaculture and animal feed, has fallen[4] with an increased reliance on crops[11]. In addition, freshwater fish production and marine shellfish production systems, together accounting for around 30% of total aquaculture production, do not rely on inputs of wild capture feeds[4]. For fed systems, technical innovation will be crucial for ensuring feed demands do not contribute to food insecurity by directing crops and water away from human consumption[11]. Greater emphasis on farming small fishes with improved fatty acid and micronutrient composition that can be eaten whole may help to allay concerns about the lower nutritional benefits of farmed fishes, invertebrates and plants[101,102]. Further progress in reducing introduction of invasive species, benthic simplification, clearance of coastal vegetation, and conflicts with other production and recreational sectors will also be fundamental to minimizing biodiversity impacts[103–106]. In addition, coherent policy development that supports aquaculture growth[107], where possible, is needed in areas experiencing cumulative agricultural and fisheries decline.

Flexible and diverse livelihood and food portfolios can help to build adaptive capacity and resilience to social and environmental change. People rely on fisheries, aquaculture and agriculture in many ways and have very varied capacity to influence or respond to changes in system productivity. While there are many tools to manage these diverse food production systems, their value and relevance in achieving SDGs is highly context specific. For example, while some relatively wealthy countries with diverse employment opportunities are focusing on obtaining high economic efficiency in fisheries (for example, Iceland[108]), economically poorer countries often focus on the provision of food and livelihoods. In these countries a diverse portfolio of household livelihoods across fishing and farming is commonly adopted as a way of maintaining food and income in economically poor coastal communities[3,94]. This diversification is expected to provide benefits in the face of climate change, especially in countries where a predicted decrease in fisheries production is countered by a predicted improvement in agricultural production or vice versa. Even in countries where agricultural and fisheries production are both predicted to decline, mixed livelihoods may help to buffer impacts, by achieving more equitable distribution of available resources nationally. However, without additional food inputs from changes in agriculture, the growth of aquaculture or imports, where feasible, these changes in livelihoods and equitability will be taking place as the total production ceiling is falling.

Effective redistribution of food to areas of deficit, waste reduction, and responsible consumption and production are needed to ensure equitable food security and nutrition. In recent decades, food insecurity has arisen not solely from failures in global food production but also from failures in distribution[105,109]. Trade reforms and efforts to overcome political barriers are relevant to food security in general[110], but will be specifically needed to catalyse effective redistribution to regions where high population growth, high fisheries dependency and the negative effects of climate on fisheries, aquaculture and agriculture are expected to interact. At present there is often an exchange between small volumes of high value fish exported from less economically developed countries and the large volumes of low value fish they import from wealthier countries[111]. Indeed, the higher the income of a country, the more valuable seafood it imports compared to its exports and vice versa[99]. This exchange is often beneficial for the less developed countries in terms of food balance and the nutritional quality of the fish received. However, in rapidly developing and wealthier countries, increasing fish demand owing to population growth and a rising middle class, may strengthen the internal market reducing the need to export. This is likely to create further demands on the food system, people and environment of already pressured poorer countries[112]. Recognizing and developing links between the provision of environmentally sustainable diets and achieving nutritional and human health policies will become increasingly important[113].

In summary, there are strong interactions and trade-offs between SDGs focusing on food, biodiversity and climate change. We have shown that analysis of the linkages between fisheries, aquaculture, agriculture and biodiversity can help to identify trade-offs and to identify countries that face combined threats or win–wins to fisheries and agriculture sectors under climate change. Coupled with information on fisheries and agricultural dependency and adaptive capacity, as indicated by the HDI, our analyses highlight nations that may face the greatest challenges when seeking to meet goals for food production and biodiversity in a changing environment. As we have seen happen in climate change adaptation, the international aid and development community, including NGOs and charities, will probably have to play a significant role in improving prospects for transition in these countries.

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Author contributions

J.L.B. and S.J. designed the study, carried out analyses and wrote the paper; R.A.W. and E.A.F. contributed to developing the paper through ideas, analyses and figures; N.K.D. and L.N.K.D. provided interpretation and access to marine biodiversity threat data. J.D., J.E. and C.M. provided interpretation and access to agriculture and Earth system multi-model ensemble outputs. D.T., H.K.L., T.D.E., M.B, A.B., W.W.C., E.G., D.C. and O.M. provided interpretation and access to marine fishery climate change multi-model ensemble outputs. All authors provided comments on the text and figures that helped to develop the paper.

Competing interests

The authors declare no competing financial interests.

Additional information

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