



Climate change, tropical fisheries and prospects for sustainable development

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Abstract | Tropical fisheries substantially contribute to the well-being of societies in both the tropics and the extratropics, the latter through ‘telecoupling’ — linkages between distant human–natural systems. Tropical marine habitats and fish stocks, however, are vulnerable to the physical and biogeochemical oceanic changes associated with rising greenhouse gases. These changes to fish stocks, and subsequent impacts on fish production, have substantial implications for the UN Sustainable Development Goals. In this Review, we synthesize the effects of climate change on tropical marine fisheries, highlighting the socio-economic impacts to both tropical and extratropical nations, and discuss potential adaptation measures. Driven by ocean warming, acidification, deoxygenation and sea-level rise, the maximum catch potential of tropical fish stocks in some tropical exclusive economic zones is projected to decline by up to 40% by the 2050s under the RCP8.5 emissions scenario, relative to the 2000s. Climate-driven reductions in fisheries production and alterations in fish-species composition will subsequently increase the vulnerability of tropical countries with limited adaptive capacity. Thus, given the billions of people dependent on tropical marine fisheries in some capacity, there is a clear need to account for the effects of climate change on these resources and identify practical adaptations when building climate-resilient sustainable-development pathways.

Landed value

The value of marine fish catches when removed from vessels in domestic or foreign ports.

Exclusive economic zones (EEZs)

A 200-nautical-mile region from a nation's coast over which a country has the sovereign right to explore and exploit, conserve and manage living and non-living resources in the water column and on the seafloor, as prescribed by the 1982 United Nations Convention on the Law of the Sea.

Marine fisheries contribute substantially to the well-being of people and society, particularly in the tropics, where coastal communities depend on fisheries for food security, livelihoods, economic development and culture^{1–3}. About 1.3 billion people live in tropical coastal areas, many of which rely on fisheries for food^{4–6}. Indeed, fish is of major nutritional importance for both coastal and urban communities in many small island developing states (SIDS), contributing 50–90% of dietary animal protein in Pacific Island countries and territories (PICTs)⁷, compared with 50% in West Africa^{8,9} and 37% in Southeast Asia¹⁰. Communities in these regions are further highly dependent on wild-caught fish for micronutrients, such as zinc, iron and omega-3 fatty acids^{2,8}, to avoid the ‘hidden hunger’ that results from micronutrient malnutrition⁹.

Tropical marine fisheries also make a significant contribution to the global fish catch. Between 2007 and 2016, for example, ~50% of the annual global fish catch (worth an average of US\$96 billion) was derived from tropical marine fisheries¹¹. Such fisheries also underpin the economies of many SIDS^{10,12}. For instance, the landed value of the four main tuna species caught in the western and central Pacific Ocean was US\$6.0 billion in 2018 (REF.¹³). Moreover, tuna-fishing license fees paid

mainly by the distant-water-fishing nations to operate in the exclusive economic zones (EEZs) of several PICTs provide 30–90% of all (non-aid) government revenue¹⁴. It is not only large-scale industrial fisheries that are important, however. Small-scale fisheries contribute ~29% (US\$31 billion) of the total landed value of fish in the tropics¹¹ and involve ~90% of the estimated 216 ± 6 million people¹⁵ employed in marine fisheries¹². Thus, in regions where employment opportunities are limited, industrial-scale and small-scale tropical fisheries provide numerous opportunities for coastal communities to earn income through harvesting and post-harvest operations^{15–18}.

Tropical marine fisheries also provide benefits for people in extratropical societies through ‘telecoupling’ (REF.¹⁹) — that is, environmental and socio-economic interactions between two or more linked areas over distance²⁰ (FIG. 1). Telecoupling interactions between tropical fisheries and elsewhere include distant-water fishing, the international seafood supply chain, trans-boundary fisheries resources and their governance. Any changes in the tropics, therefore, have the potential to propagate globally.

Indeed, the livelihoods dependent on tropical fisheries are increasingly threatened by multiple

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Key points

- Tropical oceans will be where many of the first anthropogenic signals in physical and biogeochemical variables will exceed natural variability, with resulting impacts on socioecological systems.
- Maximum catch potential in some tropical exclusive economic zones is projected to decline by up to 40% by the 2050s under continued high greenhouse gas emissions.
- Climate change impacts on tropical fisheries will affect sustainable development of both local economies and communities, and extratropical regions through ‘telecoupling’ of human–natural systems such as seafood trade and distant-water fishing.
- The key impacts for developing tropical nations will be reduced capacity to achieve the UN Sustainable Development Goals related to food security (SDG2), poverty alleviation (SDG1) and economic growth (SDG8).
- Effective and practical adaptation solutions for both small-scale and industrial fisheries, built on the involvement of all appropriate stakeholders and supporting policies, are needed to sustain fisheries productivity in the tropics.
- Many substantial predicted biological and socio-economic impacts on tropical fisheries would be prevented if greenhouse gas-mitigation actions keep global atmospheric warming below 1.5 °C relative to pre-industrial levels.

RCP2.6

Strong CO₂ emission mitigation results in falling greenhouse gas concentrations and total radiative forcing of 2.6Wm⁻² by 2100 (relative to 1750), leading to global increases in mean surface air temperature of 1.3–1.9 °C.

RCP8.5

No CO₂ mitigation leads to total radiative forcing of 8.5Wm⁻² by 2100 (relative to 1750), increasing global mean surface air temperature by 4.0–6.1 °C, an outcome resembling the A1F1, A2 and A1B scenarios included in previous Intergovernmental Panel on Climate Change reports.

factors: overfishing^{21,22}, habitat degradation²³, pollution²⁴, sedimentation^{25,26}, invasive species²⁷, as well as various physical and biogeochemical responses to climate change, including warming, sea-level rise, deoxygenation, acidification and altered nutrient concentrations. These latter CO₂-driven changes to the ocean — which are expected to increase in the coming decades — affect the physiology, behaviour and interactions of both coastal and oceanic tropical marine fish species, leading to changes in their spatial distribution and abundance^{28,29}. The very high vulnerability of tropical marine fisheries to climate change³⁰ could, therefore, undermine efforts to build sustainable development pathways for societies that depend strongly on the benefits from these fisheries, both within and outside of the tropics^{31,32}. Thus, there is an urgent need to comprehensively understand the risks of climate change to tropical fisheries to better inform adaptation measures.

In this Review, we consider the effects of climate change on tropical marine fisheries and discuss how these changes affect the use of fish in extratropical regions. The climate adaptation and mitigation measures most needed for tropical marine fisheries are described, highlighting options that could both support effective action and reduce the risk of adverse consequences on

the tropical marine fisheries sector and their dependent human communities. The implications of climate change for sustainable development goals are also addressed. Throughout this Review, the tropical regions are defined as those between the Tropic of Cancer and the Tropic of Capricorn.

Climate impacts on tropical fisheries

Climate change threatens tropical marine fisheries, and, in turn, the communities and economies that depend on those resources, both within and outside the tropics. Here, we begin by outlining the physical and biogeochemical changes associated with anthropogenic warming, followed by the response of tropical marine fish resources to these changes.

Physical and biogeochemical changes. Tropical marine fisheries are increasingly exposed to changes in the physical and biogeochemical properties of the ocean (including warming, sea-level rise, deoxygenation, acidification and altered nutrient concentrations), attributed to rising concentrations of anthropogenic greenhouse gases, in particular, CO₂ emissions^{33–35}. Indeed, tropical oceans are among the first places to show the emergence of anthropogenic signals of climate change, that is, variation in physical and biogeochemical variables exceeding the historical natural range^{36–38}. As many socioecological systems are adapted to natural variability, any changes in ocean properties outside the normal range of observed natural variability will trigger impacts that have not occurred in the recent past³⁹.

For instance, the ocean is warming because it absorbs >90% of the excess energy accumulated through rising anthropogenic greenhouse gas concentrations^{40,41}. Since the beginning of the twentieth century, for example, the sea-surface temperature (SST) in the tropical ocean has risen by ~0.75 °C (REFS^{34,42}), with accelerated warming observed since 1980 (REF⁴³). Tropical ocean warming is expected to continue and amplify throughout the twenty-first century (REF³⁶). By 2100, for instance, projections under RCP2.6 and RCP8.5 indicate that tropical SSTs will be 0.8 ± 0.3 °C and 2.9 ± 0.6 °C higher than the 1986–2005 average, respectively⁴⁴. However, even larger SST changes are expected in the equatorial Pacific compared with the southern subtropics, owing to changes in regional wind patterns and ocean circulation⁴⁵.

Superimposed on the long-term warming are short-term extreme warm temperature events, so-called marine heatwaves⁴⁶, which have devastating impacts on marine ecosystems^{47,48}. During the strong El Niño events of 1997–1998 and 2015–2016, for example, extreme ocean temperatures in the tropics and subtropics triggered unprecedented pan-tropical mass bleaching of corals⁴⁹. The number of marine heatwaves days exceeding the 99th percentile have doubled in frequency over the period 1982–2016 and now occur four times a year, in contrast to twice a year in 1982 (REF⁵⁰). Although better understanding of the physical drivers is still needed for forecasting marine heatwaves effectively⁵¹, they are projected to be 20 and 50 times more frequent under RCP2.6 and RCP8.5, respectively, when comparing 1850–1900 to 2081–2100, with the largest changes expected in the

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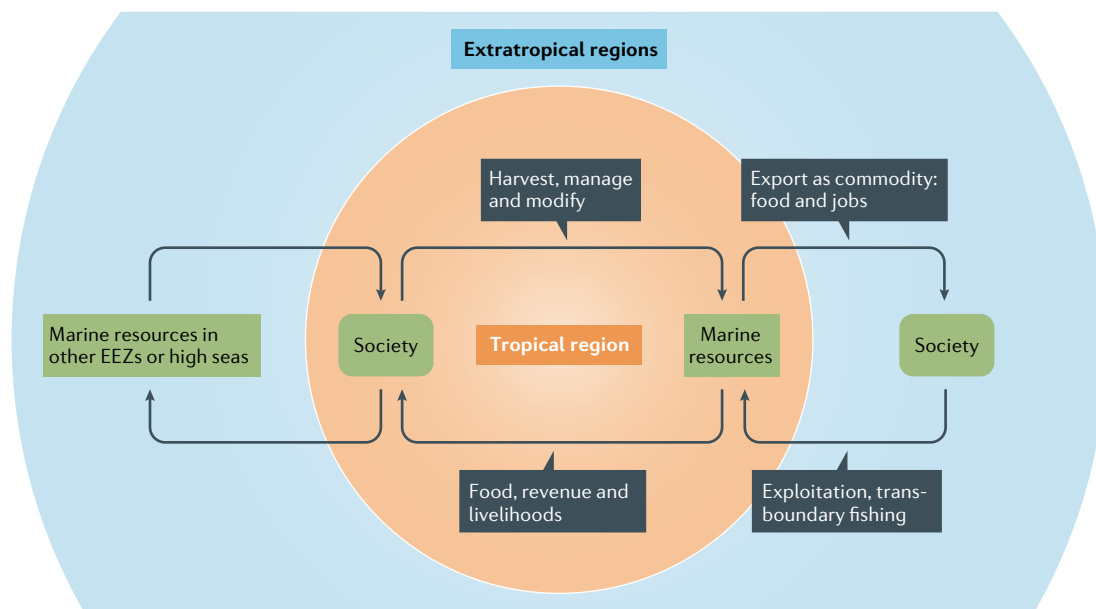


Fig. 1 | **Telecoupling linkages between tropical marine fisheries and extratropical regions.** These linkages enable the flow of benefits, including food, livelihoods and government revenue, from tropical fisheries to extratropical locations. Fish from the tropics sold in temperate-zone markets provides jobs and revenue to tropical nations. That flow of benefits is threatened by the larger impact of climate change on tropical fishery systems. EEZs, exclusive economic zones.

tropics^{34,52}. Extreme El Niño events, which also represent a form of marine heatwaves, are also projected to increase over the course of the twenty-first century under both RCP2.6 and RCP8.5 (REFS^{52–54}).

Warming of the tropical ocean also increases stratification of the upper water column^{44,55}, thereby, reducing the exchange of oxygen-rich and oxygen-depleted water bodies above and below the thermocline, respectively. As the solubility of oxygen is reduced in warmer waters, these changes have decreased oxygen content by 0.09–0.34 $\mu\text{mol kg}^{-1} \text{year}^{-1}$ for 300–700 m depths since the 1950s, also strengthening the oxygen gradient between the surface and the subsurface ocean layers^{56–59}. Over the same time period, oxygen minimum zones — regions in the water column with the lowest oxygen concentrations, which are located in eastern parts of the tropical Pacific and Atlantic Oceans and the Arabian Sea — have expanded by 3–8% per decade^{58–60}. While projected changes in oxygen minimum zones are uncertain^{61,62}, total oceanic oxygen content is projected to decline by 1.6–2.0% under RCP2.6 and 3.2–3.7% under RCP8.5 by 2100 (REF.³⁴).

The ongoing oceanic uptake of anthropogenic CO_2 from the atmosphere has also increased the acidity of tropical and other waters^{34,63}. For example, the ocean surface-water pH has decreased by 0.013–0.03 units per decade over the past 25 years (REF.⁴⁴), with the largest changes observed in the eastern equatorial Pacific and the Indian Ocean³⁶. Surface ocean pH is projected to fall by 0.03–0.042 units (REF.⁶¹) and the seasonal amplitude of global mean surface ocean pH to increase by $16 \pm 7\%$ by 2100 under RCP8.5 relative to present-day values⁶⁴. As a consequence, extreme ocean-acidity events will also become more frequent, more intense and last longer under increasing atmospheric CO_2 concentrations⁶⁵.

Rising sea levels — caused by thermal expansion of the ocean, changes in ocean dynamics and loss of land ice — also pose a threat to many tropical fish habitats, such as mangroves, seagrasses and coral reefs⁶⁶. Sea levels have risen in all tropical ocean basins and are projected to continue in the twenty-first century^{66–72}. The threats to coastal habitats and fisheries from sea-level rise are exacerbated by increases in coastal extreme events, such as tropical cyclone winds and rainfall.

Changes in net primary production. The marine food webs that support fisheries in oceanic and coastal areas are based on the net primary productivity (NPP) of phytoplankton, which, in turn, is dependent on an adequate supply of nutrients, light and appropriate temperature. However, increased stratification of the water column, owing to upper ocean warming and freshening (increased precipitation), might inhibit the supply of nutrients to the photic zone (surface waters)^{73,74}, as observed in the tropical Pacific^{74,75}. In combination with changes in light, nutrients, grazing and SST, such ocean-stratification changes are projected to decrease tropical NPP by 7–16% under RCP8.5 by 2100 relative to 2006–2015 (REF.⁴⁴), consistent with global reductions of <10% (REFS^{61,75,76}). The warming-related decrease in NPP is projected to be amplified at higher trophic levels, resulting in a larger percentage decrease in fisheries catch than is accounted for by effects on NPP alone⁷⁶.

Changes in marine ecosystems. Physical and biogeochemical stressors are also affecting the distribution, abundance and reproduction of fish and invertebrate species, via ecosystems, with direct and indirect effects on the production of marine fisheries^{39,77}. Coral reefs, mangroves and seagrasses — which provide feeding areas

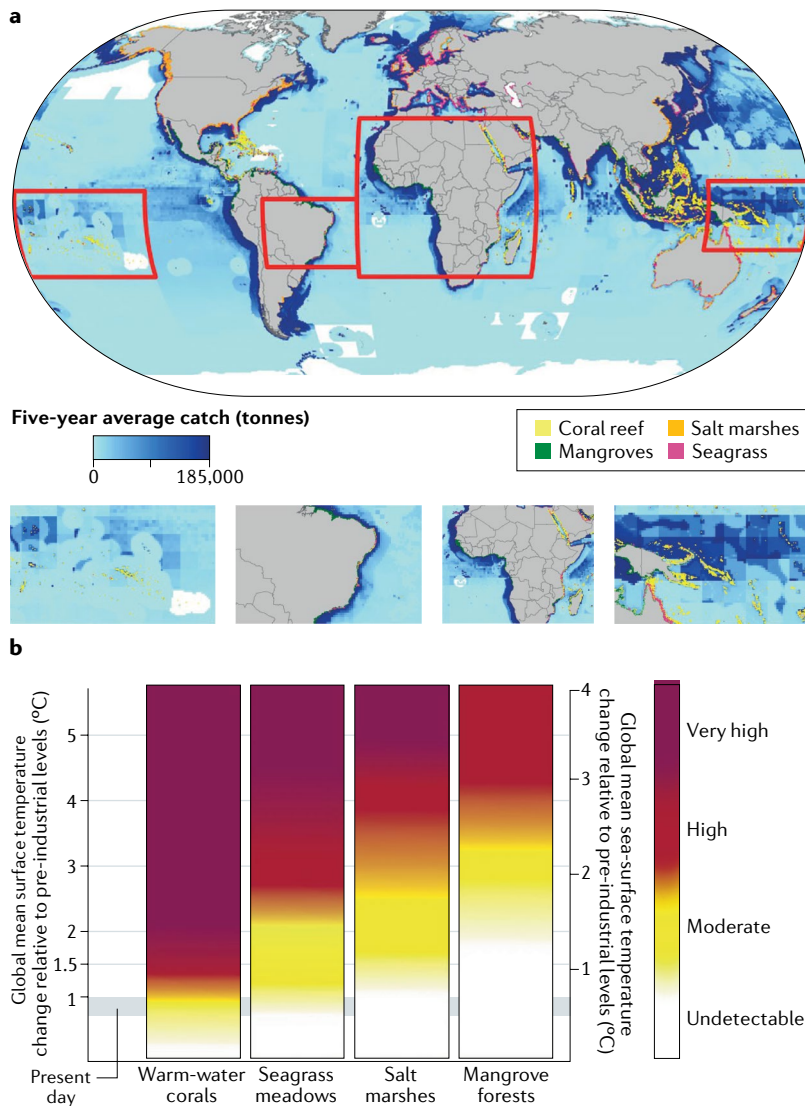


Fig. 2 | Climate change impacts on fish habitats and coastal fisheries. a | Spatial distribution of warm-water corals, seagrass, salt marshes and mangrove forests^{216–219}, and 5-year annual average catch of marine species¹⁰⁵. **b** | Level of risk posed by climate change to the four coastal ecosystems, as derived from expert judgement (Supplementary Table 3). The four major coastal habitats are highly vulnerable to climate change. These habitats have already been affected by warming and are projected to continue to be reduced in area under projected increase in temperature, with impacts on the marine ecosystems supporting fisheries. In panel **b**, ‘undetectable’ represents impacts/risks are undetectable; ‘moderate’ represents impacts/risks are detectable and attributable to climate change with at least medium confidence; ‘high’ represents significant and widespread impacts/risks; and ‘very high’ represents very high probability of severe impacts/risks and the presence of significant irreversibility or the persistence of climate-related hazards, combined with limited ability to adapt owing to the nature of the hazard or impacts and risks. Part **a** adapted with permission from Figure 5.17 of REF.³⁶, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, IPCC. Part **b** adapted with permission from Figure 3d of REF.⁴⁴, *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*, IPCC.

and habitats for part or all of fish lifespans — illustrate examples of such ecosystems vulnerable to anthropogenic stressors, including marine heatwaves^{48,50} (FIG. 2a).

Coral reefs, which often dominate tropical coastal fish habitats, are among the marine ecosystems most vulnerable to ocean warming. The majority of reef-building corals are already near their upper thermal

limits⁷⁸, and the median return time between pairs of severe-coral-bleaching events has diminished steadily since 1980 to 6 years (REF.⁷⁹). Even if anthropogenic warming is limited to 1.5°C, 70–90% of existing reef-building corals are expected to be lost by the end of the century⁸⁰. In addition, ocean acidification is reducing calcium carbonate saturation levels, limiting coral capacity to build calcareous skeletons. Indeed, the critical threshold for chronic effects of climate change on coral reefs might already have been (or soon will be) reached⁸⁰ (FIG. 2b). Similarly, half the world’s coastal wetlands, including seagrass meadows, salt marshes and mangroves, are thought to have been lost since the nineteenth century⁸¹ through climatic and non-climatic drivers^{48,50}. There is high confidence that these ecosystems will continue to be lost through warming and sea-level rise, with some estimates of 20–90% loss by the end of the century, depending on the emission scenario³⁶ (FIG. 2b).

Much like corals, marine ectothermic species (including all fishes and invertebrates) can only grow, reproduce and survive within specific temperature ranges, as determined by their physiology and ecology⁸². For tropical marine species, these thermal tolerances are more limited than temperate species⁸³, making them particularly sensitive to ocean warming⁸⁴. As a result, the distribution of many marine fishes and invertebrates has shifted polewards, to deeper waters or to follow ocean isotherms^{85,86}, where the prevailing environmental conditions (particularly temperature) favour growth and survival^{85,86}. Observed and projected distributional shifts are estimated to be 30–130 km per decade polewards and 3.5 m per decade towards deeper waters^{86–92}. These projected range shifts away from the tropics might decrease species richness in areas where environmental conditions have exceeded the tolerance limits of endemic species⁸⁶.

The aerobic capacity of fishes and invertebrates is also affected by decreasing water oxygen content and its interactions with ocean warming^{93,94}. Ocean deoxygenation can limit important metabolic functions that impair growth and reproduction in fishes and invertebrates, as well as reducing their temperature tolerances and, thus, geographic ranges^{95–97}. Ocean warming and deoxygenation also reduces the body size of some marine fishes and invertebrates, particularly in the tropics^{98–101}. For example, the average maximum body size of marine fish in the tropics is projected to decrease by ~20% by 2050 relative to 2000 under RCP8.5 (REF.¹⁰¹).

Collectively, the various stressors associated with climate change have widespread effects on tropical fisheries resources³⁶. Thus, direct and indirect effects of continued greenhouse gas emissions are expected to substantially reduce the biomass of living marine resources in the tropics¹⁰². For example, projections from global-scale models of fisheries and marine ecosystems indicate that the total marine animal biomass in the tropics will decrease by 7.3 ± 3.1% under RCP2.6 and 23.2 ± 9.5% under RCP8.5 by 2100, relative to the 2000s³⁶. Such decreases in animal biomass are largely driven by ocean warming and the decline in NPP in tropical waters resulting from climate change¹⁰³, illustrating a substantial risk to marine stocks.

Changes in marine fish stocks. Global marine fish catch has averaged between 80 and 91 million tonnes per year since 1990 (REFS^{104,105}), with mean gross revenues fluctuating around US\$100 billion annually¹⁰⁶. These values

do not include unreported catches, and the ‘true’ annual average global fish catch is estimated to be 100–130 million tonnes since the 1980s¹⁰⁵. However, after reaching its peak in the 1990s, fish catches have been declining and seem to have levelled off because many fish stocks are considered to be either fully exploited or overexploited (that is, spawning biomass is below the reference values to achieve maximum sustainable yield)^{104,107–113}. Tropical fisheries have also expanded rapidly: annual catch has increased from 7.1 million tonnes (US\$7.3 billion) in the 1950s to 50 million tonnes in 2016 (US\$89.7 billion), and the annual average catch estimates become 53.6 million tonnes when unreported catches are taken into account^{104,105}.

However, climate change threatens these fish stocks. Changes in temperature and phytoplankton production are related to the changes in fisheries catches and species composition in many tropical marine ecosystems since 1950 (REFS^{114–116}). Furthermore, analysis of fish-population data shows that the maximum sustainable yield of 235 fish populations over 38 ecoregions has been reduced by 4.1% over the past 80 years (REF¹¹⁶), and increases in SST have led to negative changes in marine fisheries production in 8 of 47 large marine ecosystems between 1998 and 2006 (REF¹¹⁴). Historical catch data from tropical ecosystems also show substantial increases in the dominance of warm-water-tolerant species since the 1970s that are related to ocean warming^{116,117}.

These observed changes are also projected to continue and amplify in the future. Global impact models, for example, predict decreases in maximum catch potential (MCP) of up to 40% in some tropical EEZs by the 2050s³³ (FIG. 3a,b). The decrease in catch potential, driven largely by ocean warming and decrease in NPP, is projected to be particularly large in tropical Pacific and eastern tropical Atlantic regions under the high-emissions scenario. For instance, in the Indo-Pacific region, 3.5 °C atmospheric warming is projected to decrease maximum catch potential by 46.8 ± 1.2%, as well as cause species turnover of 36.4 ± 2.1% (REFS^{31,118}). In the tropical Pacific region, more than half of the (mainly coastal) fish and invertebrate species important to fisheries are also projected to become locally extinct by 2100 under RCP8.5 (REFS^{29,44}), contributing to the large decrease in the catch potential. Overall, by 2100, changes in biomass, catch potential and species composition are projected to be 2–4 times greater under RCP8.5 compared with RCP2.6 (REF³⁴). Similarly, an index that integrates the projected effects of ocean warming, deoxygenation and acidification for exploited fish stocks in the tropics indicates that the

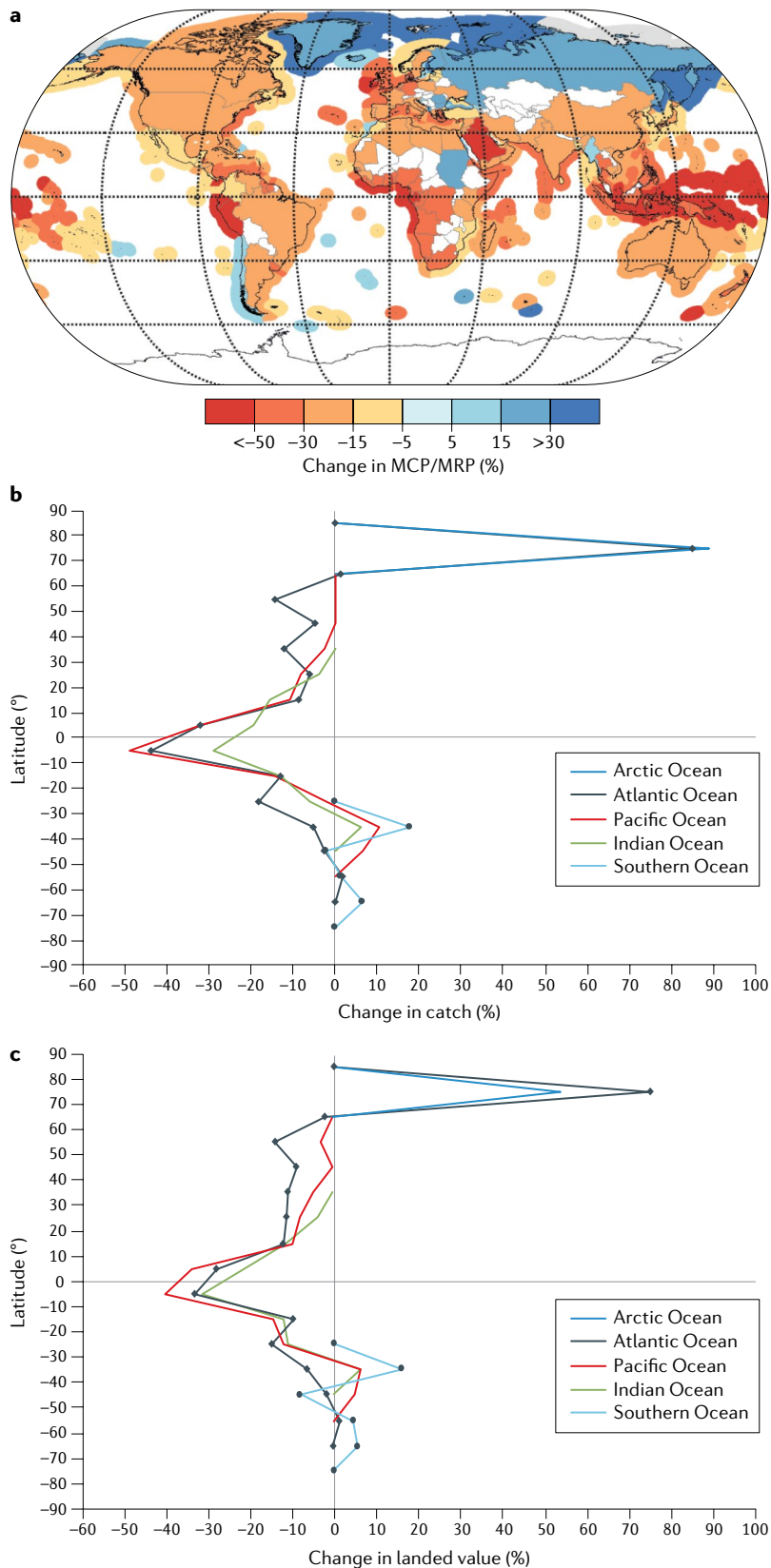


Fig. 3 | Climate change impacts on maximum catch potential and maximum revenue potential. a | Mean percentage change in maximum catch potential (MCP) and maximum revenue potential (MRP) for 2041–2060 relative to 1991–2010 under Representative Concentration Pathway 8.5. **b** | Zonally averaged projected changes in MCP based on data in panel a for the major ocean basins. **c** | Zonally averaged projected changes in MRP based on data in panel a for the major ocean basins. The greatest declines in MCP and MRP are found in tropical regions of the Pacific, Atlantic and Indian Oceans. Parts a and c reprinted from REF³¹, CC BY 4.0.

Box 1 | Fisheries in the Pacific Islands region

Across the 22 Pacific Island countries and territories (PICTs), models predict an eastern redistribution in the biomass of skipjack and yellowfin tuna — the two main exported fish species — by 2050 (REFS^{28,158,220–222}). Under Representative Concentration Pathway (RCP) 8.5, for example, the combined catch of both tuna species is projected to decrease by ~10–40% by 2050 in the exclusive economic zones of Federated States of Micronesia, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands, Tokelau and Tuvalu^{123,222}. However, given the eastern redistribution, tuna catch is anticipated to increase in the exclusive economic zones of Kiribati and Cook Islands by 15–20% (REFS^{123,222}).

As several PICTs are tuna-dependent economies¹²³, the impact of climate change on tuna fisheries increases the vulnerability of these small island developing states^{124,223,224}. For instance, shifts in tuna distribution, and resulting increases in catches from international waters²²², are expected to cause proportional changes in government revenue received by small island developing states from fishing licence fees^{123,224}. These changes need to be considered by the Western and Central Pacific Fisheries Commission when governing the sustainable use of the region's tuna resources^{147,225}, developing harvest strategies²²⁶ and allocating fishing rights to minimize the implications of tuna redistribution for island economies.

The projected 20–50% decrease in productivity of coral reef fish in the Pacific Islands region by 2050 under RCP8.5 (REFS^{29,227}) is expected to influence the contributions of small-scale fisheries to food security in most PICTs^{7,224}. However, rapid population growth in several PICTs is expected to have a greater influence than declining reef fish production on future availability of fish per capita^{223,224}. The rich tuna resources of the Pacific Islands region can be used to fill the widening gap between the total amount of fish that can be harvested sustainably from coral reefs and other coastal habitats, and that required for good nutrition^{122,157}.

risk of impacts increases from moderate-to-high under RCP2.6 to very high risk under RCP8.5 (REF¹¹⁹).

Effects on communities and economies. The previously discussed impacts of climate change on tropical ecosystems and fish stocks will have profound economic¹²⁰ and social¹²¹ effects. In the absence of improved management, marine fisheries revenues are projected to decline in 89% of the world's fishing countries under RCP8.5 by 2050, relative to their current status³¹. The greatest negative impact on maximum revenue potential (MRP) is in tropical regions, with EEZs in the central Pacific and central Atlantic being affected the most (FIG. 3c). The MRP is projected to decline by an average of 33% in the tropics by the 2050s under RCP8.5 (REF³¹) (FIG. 3c). The EEZs with the largest average decrease in MCP mostly belong to SIDS³¹. However, projected reductions in MCP in a country's EEZ do not necessarily translate to proportional losses in revenue³¹, for example, if national vessels fish not only in their own EEZs but also in those of other countries or in international waters.

The implications of climate change for the socio-economic benefits derived from fisheries also vary by region, with the greatest effects occurring in low-income, food-deficit tropical countries, including SIDS, African and Asian countries or regions, for example, West Africa and Southeast Asia³¹. These developing countries usually rely heavily on fish and fisheries as a major source of micronutrients for healthy diets, as well as for livelihood and employment opportunities^{122,123}, but have a relatively low capacity to adapt^{121,124}. Therefore, adverse effects of climate change on the catch and total fisheries revenues in these countries are proportionally greater than in countries with a high human development index and a large, diverse economy^{2,125}.

Climate change might also lead to the loss of 10–40% of species suitable for marine aquaculture in the tropics and subtropics by 2050 (REF¹²⁶). The losses in richness of potential mariculture species are projected to be higher throughout much of the tropics under climate change^{126–128}, particularly impacting Asian countries that contribute the most to mariculture production. Furthermore, the potential area suitable for tropical mariculture is estimated to decline by $3.69\% \pm 0.59$ by the 2090s under RCP8.5, relative to the 66 million km² available in the 2000s¹²⁶, limiting the scope for seafood production expansion needed to meet growing demand.

Examples of the expected effects of climate change on fisheries resources and on the socio-economic benefits they provide for communities and economies in PICTs, Brazil and coastal African nations are included in BOX 1, BOX 2 and BOX 3, respectively. Fisheries reform has the potential to offset the consequences of climate change, however. Indeed, addressing current inefficiencies, adapting to changes in productivity and implementing improvements in institutional management could provide benefits exceeding the adverse effects of climate change and drive net increases in yields and profits¹²⁹.

Telecoupling to the extratropics

Seafood is the most highly traded food commodity globally^{104,130}. Trade has increased in recent decades due to greater demand and willingness to pay for high-quality produce¹³¹. Tropical nations often gain considerable benefits from this international trade, especially in exporting countries that have low per-capita fish consumption but large offshore fisheries (such as Namibia) or where the rate of production from wild-caught fisheries has increased faster than local demand for fish (such as in Ghana, Thailand and the Philippines)¹³². The partial dependence of developed extratropical countries on tropical fisheries resources exposes them to the consequences of climate change in tropical regions via telecoupling (FIG. 1). For instance, the projected declines in MCP of up to 40% by the 2050s for many fish species, combined with increased demand for seafood by many tropical developing countries due to economic growth, could reduce the future supply of seafood to extratropical countries³¹. Much of the trade involves high-value species (especially tuna, Supplementary Table 1) exported from developing tropical countries to developed extratropical nations^{130–133} (FIG. 4). During 2015–2017, for example, ~46% of fish caught by Caribbean countries was exported to North America, and 20% to the European Union¹³⁴.

However, low-value, small pelagic fish, such as anchovies and sardines, also represent a major proportion of fish exports, especially in South America, West Africa^{135,136}, Thailand and Vietnam¹³⁷. These fish, caught in tropical areas, are often converted to fishmeal, a key component of feeds for the aquaculture of salmon, trout and shrimp, traded internationally in the extratropics^{138,139}. Indeed, in 2016, ~12% of marine fisheries production was used for non-food purposes, of which 74% (~15 million tonnes) was converted to fishmeal and fish oil^{104,140}. Although climate change models predict that marine ecosystems should continue

Maximum sustainable yield

The highest possible annual catch that can be removed from a population while keeping the maximum growth over a long period of time. The maximum sustainable yield refers to a hypothetical equilibrium state between the exploited population and the fishing activity.

Maximum catch potential

(MCP). The potential of the fish stocks to provide long-term fish catches; it is considered a proxy of the maximum sustainable yield.

Species turnover

The number of species locally extinct and newly established in a particular area, used to represent the extent of changes in the species assemblage.

Representative Concentration Pathway

(RCP). Four climate change scenarios are included in the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Only scenarios with the highest (RCP8.5) and lowest (RCP2.6) radiative forcing are mentioned in this Review.

Maximum revenue potential (MRP). Landed values at the maximum catch potential.

Human development index
A summary measure of average achievement in key dimensions of human development: a long and healthy life, being knowledgeable and a decent standard of living.

to produce good harvests of small pelagic fish, the sustainability and profitability of the fishmeal trade (and maintenance of its associated economic benefits for fishing communities) will depend on interactions with fisheries management, market-stabilization measures, improvements in technology, international cooperation, development of soybean-based fishmeal substitutes¹⁴¹ and implementation of global rules for seafood markets aimed at improving ecosystem health^{142–145}.

A potent example of the consequences of telecoupling on extratropical economies and communities is provided by the effects of climate-driven changes in the distribution, catch composition and catch potential of Peruvian anchoveta (a small pelagic fish used to produce fishmeal¹³⁹) on aquaculture operations in higher latitudes. Salmon aquaculture in Norway, Chile, the UK and Canada provides over 85% of global farmed salmon production¹⁴⁶ and, with the exception of Chile, these countries depend heavily on imported fishmeal, including that derived from Peruvian anchoveta¹⁴³. The pronounced effects of El Niño–Southern Oscillation (ENSO)-mediated climatic variability on annual harvests of Peruvian anchoveta led telecoupled aquaculture industries to develop mechanisms to cope with dramatic variations in the supply of anchoveta. In particular, the wild-fish component in aquaculture feed is being replaced with soybean meal, rendered terrestrial animal products and seafood or aquaculture processing wastes¹⁴². These innovations might enable the consumption of farmed fish to increase by 2050 even under RCP8.5 (REF. ¹⁴⁵), thereby, limiting the effects of climate change on the telecoupled dependence of salmon farming on Peruvian anchoveta.

Implementation of sustainable fisheries operations by distant-water fishing nations in the EEZs of many SIDS

and coastal states¹⁴⁷ delivers significant benefits for the well-being of communities and economies in tropical countries¹⁴. However, it is also important for extratropical countries. Similarly, fisheries-management legislation in extratropical countries can affect the socio-economic benefits derived from fisheries in telecoupled tropical regions. For example, the Chinese government's decision to reduce fuel subsidies by 60% and its pending legislation to improve the monitoring of Chinese vessels fishing in the EEZs of other nations are expected to reduce the high pressure exerted by Chinese vessels on fish stocks in Senegal. These measures should improve the status of marine resources in that country and the contributions of local fisheries to livelihoods and food security^{148,149}.

The effects of climate change on tropical fisheries also influence the profitability and employment opportunities of fish-processing industries in extratropical regions such as Spain, Italy, France, the USA and Japan. Spain, for example, is the most important producer of canned tuna in Europe (and the second largest globally after Thailand)¹⁵⁰, employing more than 18,000 people in 2016 (REFS^{15,151}) and responsible for the investment of hundreds of millions of Euros in the fishing and processing industries in Ecuador, El Salvador, Guatemala and Venezuela — an investment that has provided about 35,000 jobs in these countries¹⁵⁰. Raw materials for the world's tuna-processing industries are often supplied by distant-water fleets or imports from SIDS and developing countries in African, Caribbean and Pacific regions. Thus, climate-related changes in the distribution and abundance of tuna (BOX 1)^{152,153} threaten not only the national plans of SIDS and developing countries to maximize the contributions of their marine fisheries resources for food security, employment and economic development¹⁵⁴ but also investments by distant-water fishing nations in tropical developing countries.

Box 2 | Fisheries in Brazil

The south-western Atlantic Ocean is a hotspot of climate change²²⁸, with increased sea-surface temperature the most prominent climate risk to marine resources, followed by changes in ocean circulation and stratification. These physical climatic changes are anticipated to influence primary production, reducing productivity for fisheries in Brazil^{228,229}. In saline and freshwater wetlands, climate change-modified hydrological regimes, which can cause intense droughts or inundation, are expected to reduce habitat area and the abundance of fish in confined refugia²³⁰. Increases in temperature on floodplains are expected to increase the frequency and duration of hypoxic or anoxic episodes, leading to a reduction in growth rates and a mismatch in reproductive success of many species²³¹.

In fact, Brazilian fisheries have already seen changes in fish distribution, influencing livelihoods^{228,232–234}. Climate-related shift in the spatial distribution of marine species has been recorded in both coastal and offshore waters^{235–237}; some species (such as the Brazilian sardine) are moving to cooler and deeper waters, whereas others (squid) have migrated to areas with warmer winter temperatures²³⁸. Rising sea levels and hydroclimatic variability, for example, have resulted in loss of mangrove and wetland habitats²³⁹, including in the Amazon and Pantanal floodplains²³⁰, and this is expected to have knock-on effects on the production of fisheries associated with these habitats. Ocean acidification has also inhibited coastal seaweed photosynthetic pigments²⁴⁰ and the osmoregulation capacity of crustaceans such as crabs²⁴¹.

Given the large internal market for fish in Brazil, as well as increasing per-capita fish consumption, these changes will have corresponding economic impacts²²⁸. El Niño events, for example, have been responsible for economic losses of US\$9 million per year in the shrimp and mullet fisheries of South Brazil²²⁸. Moreover, climate-induced distribution shifts of some transboundary fish species may lead to conflicts between countries in the region and negatively affect international relations.

Impacts on sustainable development

Tropical marine resources support important aspects of sustainable development, specifically related to the UN Sustainable Development Goals on food security (SDG2) and economic development to eliminate poverty (SDG1). It is clear that adaptations that maintain the supply of fish for food security in tropical countries need to address both the effects of climate change on coastal fish habitats and fish stocks, as well as the effects of population growth and other socio-economic factors on the availability of fish per capita. Win–win and ‘no-regrets’ solutions (Supplementary Table 2) (that is, actions that generate net social benefits under all future scenarios and consequences of climate change¹⁵⁵) are needed^{33,122}. The Pacific Island approach (BOX 1) demonstrates that adverse effects of climate change on one marine fisheries resource can sometimes be addressed by modifying the way in which another such resource is used. Exemplary management of tuna in the western and central Pacific Ocean¹⁵⁶, for example, enables Pacific Island governments to allocate an increased, albeit still minor, proportion of the regional tuna resource to domestic food security¹⁵⁷. Importantly, climate-driven redistribution of tuna¹⁵⁸ is not expected to affect this capability

Provisioning services

Includes tangible products from ecosystems that humans make use of, such as fish and seafood, agricultural crops, timber or fresh water.

Regulating services

The benefits people obtain owing to the regulation of natural processes, such as carbon sequestration and storage, erosion prevention, waste-water treatment and moderation of extreme events.

Supporting services

The services that are necessary for the maintenance of all other ecosystem services including biomass production, life-cycle maintenance for both fauna and local, element and nutrient cycling.

Cultural services

Tourism, recreational, aesthetic and spiritual benefits.

because ample tuna is still expected to be available for this purpose¹²².

Two other implications of the Pacific Island situation stand out. First, climate justice¹⁵⁹ needs to extend to the fisheries sector because tuna-dependent Pacific Island economies produce a trivial percentage of global greenhouse gas emissions. This fact needs to be recognized and PICTs enabled to retain the important socio-economic benefits they receive from tuna¹⁴, regardless of climate-driven redistribution of tuna resources¹²³. Second, the Western and Central Pacific Fisheries Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC) will increasingly need to collaborate as climate change alters the distributions of transboundary tuna stocks. Close collaboration between these two regional fisheries-management organizations is expected to reduce the potential for conflict arising from species on the move¹⁴⁷. Moreover, improved coordination of harvest strategies across the jurisdictions of the WCPFC and the IATTC will help to ensure the sustainability of tropical Pacific fisheries resources (BOX 1).

The wide spectrum of potential climate-related changes influence the services provided by tropical marine ecosystems (including provisioning services, regulating services, supporting services and cultural services) in various ways, thereby, differentially affecting the abilities of SIDS and other developing countries to achieve their sustainable development goals^{160–162}. However, the effects of climate change on the services provided by marine ecosystems often have the largest direct effects on SDG2 (eliminating hunger)¹⁶² because declines in food production are common when marine species shift their distributions and/or decrease in biomass. However, shifts in the distribution of fish species also hinder progress towards SDG1 (poverty alleviation) and SDG8 (economic growth and job creation). Interestingly, although the projected shifts in tuna biomass within the tropical Pacific Ocean (BOX 1) are expected to make it more difficult for PICTs in the western and central Pacific Ocean (which are heavily dependent on marine ecosystems^{14,121,163}) to achieve their sustainable development goals, the same shifts are likely to boost the ability of countries in the eastern Pacific to attain theirs¹⁶¹.

Adaptation and mitigation measures

Practical and effective adaptations to assist fishers, local communities, industries and governing institutions in SIDS and other tropical developing countries to sustain their fisheries production in the face of climate-related and climate-unrelated stressors^{32,121} fall into three broad categories: ecosystem-based solutions, built-environment solutions and institutional-based or policy-based solutions. Ecosystem-based adaptations rely on the management, conservation and restoration of fish habitats and fish stocks to provide optimal ecosystem services despite climate change, including sequestration of carbon to mitigate greenhouse gas emissions^{164,165}. Built-environment adaptations^{166,167} often involve designing coastal infrastructure to cope with sea-level rise in ways that minimize barriers to the landwards migration of mangrove and sea-grass habitats^{33,122}. Institutional-based or policy-based adaptations^{168–170} include practices and policies that support climate-informed, community-based responses to sustain catches within established social governance and economic systems¹⁷¹. Additional steps are required to limit greenhouse gas emissions and, thereby, increase the likelihood that these adaptations will succeed.

Adaptation of small-scale fisheries. Various practical, cost-effective adaptations could help to maintain the contributions of small-scale fisheries to food security and livelihoods in SIDS and other tropical developing countries¹²². Whenever possible, such adaptations should address present-day factors that affect access to fish for food security, as well as the effects of climate change^{122,172} (Supplementary Table 2). ‘Win-win’ adaptations and supporting policies revolve around integrated coastal management to safeguard fish habitats, but can also include diversifying fishing methods¹²⁵. One of the examples is to support coastal communities to progressively transfer fishing effort from coral reefs and other threatened coastal habitats to large and small pelagic fish species in near-shore waters to meet shortfalls in fish supply^{122,173} (Supplementary Table 2).

Primary fisheries-management¹⁷⁴ approaches are also needed to maintain the reproductive potential of fish stocks in data-poor contexts. Improving fisheries management and rebuilding overexploited or depleted fish stocks can help alleviate climate-induced decrease in potential fisheries production on actual catches^{129,175}; however, the effectiveness of such adaptation measures is likely to be lower in many tropical developing countries, particularly in small-scale fisheries, where capacity for effective fisheries management is not ideal. As such, enhancing fisheries-management capacity, from gathering and utilizing scientific information to fisheries governance, is an important part of the portfolio of adaptation measures for tropical fisheries.

For many small-scale coastal fisheries, community-based fisheries management is an effective method of adaptation to climate change because it is based on iterative cycles of learning from and responding to changing conditions¹⁷⁶. As evidence of the potential contribution of community-based management of fisheries in vulnerable regions, the Government of Solomon Islands

Box 3 | Fisheries in African nations

Already affected by pollution, overfishing and weak enforcement of fishing regulations^{242,243}, marine ecosystems in Africa are now also threatened by various physical and biogeochemical anthropogenic stressors. While many African marine fish are more resilient to warming than species elsewhere, unprecedented coral bleaching and extensive coral mortality across most of the western Indian Ocean has decreased fisheries production and their associated benefits for communities in East Africa^{244,245}. Model simulations also predict that marine fish catches in most West African countries will decrease by >50% by 2050 under RCP8.5, with the largest reductions in countries nearest the equator²⁴⁶. Projections are, however, model dependent; for example, some predict that fish landings will decline by 8–26% (REF.²⁴⁶), whereas others project a 23.9% increase in the Gulf of Guinea by 2050 (REFS^{247,248}). Nevertheless, all models suggest that fisheries in the tropical African countries are highly vulnerable to climate change^{121,124}.

These climate-related changes are anticipated to decrease the value of landed catch by ~20% by 2050, as well as reduce fisheries-related jobs by ~50% (REF.²⁴⁶). These impacts will not only affect food security in tropical African countries but also influence other economies reliant on African fish imports. However, the consequences for local fishing communities depend strongly on their adaptive capacity^{247,249}.

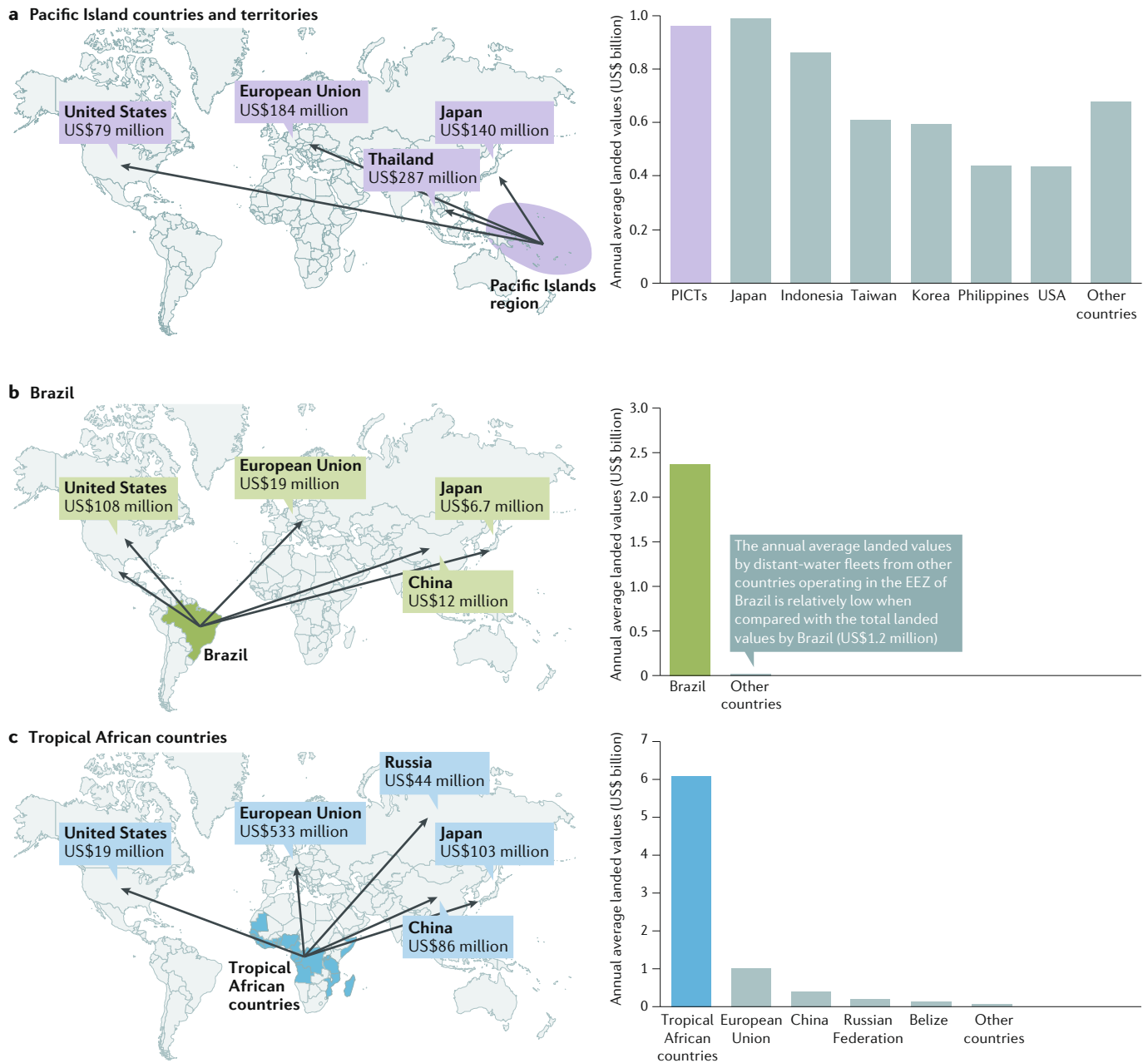


Fig. 4 | **Economic telecoupling of tropical fisheries.** Annual average value (US\$ million) of fish exports from Pacific Island countries and territories (panel a), Brazil (panel b) and Africa (panel c) to their main trading partners for 2014–2018 (left), and annual average landed values (US\$ billions) of fish caught in the three corresponding groups of exclusive economic zones (EEZs) by the countries and territories in those regions and by distant-water fishing nations between 2007 and 2016 (right). There are close linkages between the tropical regions and the extratropical nations through trade and distant-water fishing, indicating that any climate-related changes to tropical fisheries have socio-economic implications for many extratropical nations. Note that values from the Pacific Islands region are for tuna only, and the catch values refer to tuna caught from the Western and Central Pacific Fisheries Convention Area, which is larger than the combined EEZs of PICTs (see Supplementary Tables 1,4–8). Source of data for panel a: Pacific Islands Forum Fisheries Agency.

has identified community-based resource management as a key tool for building the capacity to adapt to climate change¹⁷⁷. Similarly, communities in Timor-Leste have successfully experimented with small-scale fish-aggregating devices^{178,179} as a response to changes in species distribution resulting from climate change¹⁸⁰. Community-based fisheries management requires the participation of communities and resource users in

decision-making activities and the incorporation of local institutions, customary practices and knowledge systems into management processes¹⁸¹.

Community-based management can take many forms, including locally managed marine areas, territorial user rights, customary marine tenure, taboo areas¹⁸² (spatial closures) and periodic harvesting (temporal) closures. These diverse approaches share three characteristics that

provide a foundation for effective adaptation^{176,183}. First, community-based management is often characterized by experimentation and learning, which are critical components of adaptation solutions in the context of uncertainty and change^{32,184}. For example, periodic harvesting closures, a common marine-management approach in the western Pacific, involves iterative cycles of experimentation, evaluation and adjustment¹⁸⁵. Appropriate spatial and temporal closures can help to maintain fish stocks, fisheries yield and catch efficiency, thus, building ecological resilience and reducing social and ecological vulnerability to climate change^{186,187}. Second, community-based fisheries management prioritizes local and indigenous knowledge, which is essential for climate change adaptation¹⁸⁸. For example, in the Torres Strait Islands, local knowledge about past climatic patterns has been used to design rock walls and wind breaks, as well as guide the planting of native coastal species, to reduce climate vulnerability¹⁸⁹. Third, the flexibility inherent in many community-based fisheries-management approaches supports effective adaptation. For example, changes in permitted equipment or target species enable responses to climate-driven changes arising from shifts in the range of a species or changes in abundance within its range^{190,191}.

The steps to build climate resilience in tropical fisheries through effective community-based fisheries management might involve promoting transdisciplinary collaboration, including provision of the necessary expertise to inform stakeholders about climate-driven risks to fish habitats, fish stocks and catches; facilitating the participation of these stakeholders; monitoring the wider fisheries system for the effects of climate change; and allocating resources to enable implementation of an ecosystem approach to fisheries management¹⁷¹. The contributions of community-based and ecosystem-based fisheries management to building climate resilience is mediated by how well decision-making institutions fit their socioecological conditions, effective communication processes among key stakeholders and key leaders, effective cooperation among groups and political-management skills, as well as global action on climate change^{192,193}.

Adaptation of industrial fisheries. The fisheries reform¹²⁹ to address current inefficiencies, respond to changes in productivity and improve institutional management is likely to contribute to reducing the consequences of climate change for industrial fisheries under good national governance. However, climate-driven shifts in distributions of fish species across political boundaries require higher levels of collaboration to avoid disputes that can impair the sustainability of co-managed fisheries^{147,194,195}. Some cooperative fisheries-management arrangements in the tropics are flexible enough to respond reasonably effectively to transboundary redistribution of biomass³⁴. A prime example is the 'vessel day scheme' operated by the Parties to the Nauru Agreement (Federated States of Micronesia, Kiribati, Marshall Islands, Nauru, Palau, Papua New Guinea, Solomon Islands and Tuvalu), which addresses the effects of climatic variability and climate change on the distribution of tuna stocks within

the combined EEZs of the eight countries¹²³. However, projected shifts in tuna from the combined EEZs into international waters, and an overall decrease in tuna production across the region in the long term, remain key challenges, particularly under RCP8.5 (BOX 1).

Ultimately, effective management of transboundary fish stocks in the face of climate change will depend on identifying all self-replenishing populations within the geographical range of the species, modelling the response of each population to climate change and identifying the stakeholders for each current and redistributed population^{123,196,197}. New combinations of stakeholders require the development of cooperative sustainable harvest strategies informed by changing ocean conditions. Effective management of the large transboundary stocks that underpin several tropical industrial fisheries also requires improved monitoring, modelling and decision-support frameworks. Built-environment options, such as improved climate-forecasting and advanced-warning systems, not only for the extreme events that affect fishing vessel and crew safety at sea but also for geographical shifts in biomass of target fish species, will also facilitate sustained operation of industrial fisheries, and the equitable sharing of economic benefits derived from them, as the climate continues to change³⁶.

Greenhouse gas-emission mitigation. Ultimately, the root causes of climate-driven changes in tropical marine fisheries must be addressed¹⁹⁸. Climate models indicate that mitigating greenhouse gas emissions, and keeping global atmospheric warming below 1.5 °C relative to pre-industrial levels avoids substantial biological and socio-economic effects on tropical fisheries^{118,199}. Implementation of the Paris Agreement would help to safeguard the annual global catch of high-value fish species and billions of dollars of revenue for fishers and seafood workers¹⁹⁹. Similar benefits are also expected for tropical developing countries and telecoupled extratropical countries.

Implementation by all countries of the national determined contributions stated in the Paris Agreement²⁰⁰ would help to achieve the necessary mitigation of emissions. Although many tropical developing countries produce very low levels of greenhouse gases compared with developed nations, the tropical-marine-fisheries sector can still contribute meaningfully to the global mitigation effort. The mangrove, seagrass and salt-marsh habitats that sustain fish stocks and coastal communities throughout much of the tropics are carbon sinks^{201–203} that are an important part of the portfolio of mitigation options for many tropical countries²⁰⁰. However, damage to these ecosystems due to deforestation and habitat degradation is causing 0.15–1.02 billion tonnes of CO₂ to be released annually²⁰⁴. These emissions are equivalent to 3–19% of those caused by global deforestation and result in economic damage of US\$6–42 billion annually²⁰⁴. Protection of mangrove, seagrass and salt-marsh ecosystems is imperative to maintain their capacity to remove greenhouse gas from the atmosphere³⁶. In Columbia, mangroves and seagrasses in marine protected areas account for 49–94% of the nation's annual carbon capture and provide economic benefits totalling €44–295

million per year²⁰⁵. Small-scale fisheries have potential roles as carbon stewards in projects designed to deliver payments for ecosystem services^{206,207}, although skeptics suggest that such schemes only facilitate ‘ocean grabbing’ and effectively cede control of coastal ecosystems to transnational companies seeking to offset their carbon emissions²⁰⁸. Thus, although the climate-adaptation and climate-mitigation measures taken by the tropical-marine-fisheries sector offer much potential for success, their effectiveness will depend on strong mitigation of greenhouse gas emissions and socio-economic conditions that support an adequate adaptive capacity¹⁹⁸.

Small-scale fisheries, industrial fisheries and aquaculture operations in tropical countries (and globally) also have a role to play in reducing greenhouse gas emissions. Practical adaptations enabling the sector to do this have been assembled by the Food and Agriculture Organization of the United Nations (FAO)³³. Fisheries improvements ranging from increasing the efficiency of fishing boats to adjustment or adaptation of fishing methods are also considered as useful mitigation measures for tropical small-scale fisheries. Greenhouse gas emissions from small fishing vessels can be reduced by the use of more efficient engines, larger propellers, improved vessel shapes and simply by reducing the mean speed of vessels³³. Where small-scale tuna fisheries are needed to increase fish supply and ensure food security in SIDS, emissions can be reduced by fishing around fish-aggregating devices anchored close to the coast²⁰⁹.

Summary and future perspectives

Tropical fisheries have an important role in supporting food security and livelihoods in tropical countries and in extratropical regions through socio-economic telecoupling (for example, via distant-water fishing and seafood trade). The direct and indirect effects of climate change are projected to impair tropical marine ecosystems and fisheries, reducing their contributions to human well-being. To reduce the effect of greenhouse gas emissions on the benefits derived from tropical fisheries, both locally and in non-tropical regions, the root causes of climate-driven fisheries problems now evident in the tropics need to be recognized and rectified. Effective climate change adaptation and mitigation solutions require stakeholder commitment and involvement, as well as appropriate supporting policies.

The science linking physical changes (warming and sea-level rise) and biogeochemical alterations (acidification and deoxygenation) to the ocean to the

physiological and ecological responses of fish species is developing rapidly and giving rise to more robust predictive models. However, there is an urgent need to identify robust, practical adaptations to maintain the vital contributions that tropical fisheries make to communities and economies as the abundance and distribution of fisheries resources are rearranged by continued greenhouse gas emissions. Until global emissions conform to levels that will limit warming to 1.5 °C, it is also essential that policy frameworks are developed to support priority adaptations.

These policy frameworks must embrace entire supply chains because even local, small-scale fisheries are connected to large marine ecosystems and global trading networks through diverse and multiscale linkages. This complexity poses challenges for the design of science-based adaptations and supporting policies — the responses of fishers and workers in seafood industries to perceived change can be reactive or proactive, autonomous at the individual level or collective, and planned or unplanned²¹⁰. These adaptations and policies can be steered effectively by the widely endorsed FAO guidelines for sustaining small-scale fisheries²¹¹.

Understanding the societal impacts of climate change on fisheries and guiding effective adaptive responses requires scientists to step outside their existing interdisciplinary collaborative frame (which is typically limited to Earth and ocean sciences, ecology and economics) to include the study of geopolitical policy, knowledge accrual and communication, human agency, values and behaviour^{212,213}. Including these fields in future research will improve the science and policy communities’ understanding of the effects of climate change and improve the knowledge and perception of climate change and fisheries by fishing communities, allowing them to integrate this understanding with their value systems, incentives and capacities to adapt³². Explicit consideration of ethical values in the human–Earth relationship is already attracting increased attention in the Earth sciences²¹⁴. Geoethics and human-rights-based governance of small-scale fisheries have been compared²¹⁵, pointing to a promising convergence of these disparate fields. This enlarged Earth system science, guided by an emergent emphasis on geoethics, may be better placed to serve humanity’s transition to sustainability in the Anthropocene, including a transition to sustainable and resilient fisheries in a changing climate.

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Author contributions

All authors contributed to writing the article. In addition, V.W.Y.L. and J.D.B. researched data for the article, V.W.Y.L.,

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