FRONT MATTER

Title

- *Full title:* Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries
- *Short title:* Climate change impact on agriculture and fisheries

Authors

Lauric Thiault[1,2], Camilo Mora[3], Joshua E. Cinner[4], William W. L. Cheung[5], Nicholas A.J. Graham[6], Fraser A. Januchowski-Hartley[7,8], David Mouillot[4,7], U. Rashid Sumaila[9], Joachim Claudet[1,2]

Affiliations

[1] National Center for Scientific Research, PSL Université Paris, CRIOBE, USR 3278 CNRS-EPHE-UPVD, Maison des Océans, 195 rue Saint-Jacques, 75005 Paris, France.

[2] Laboratoire d'Excellence CORAIL, Moorea, French Polynesia.

[3] Department of Geography, University of Hawai'i at Manoa, Honolulu, Hawai'i 96822, USA.

[4] Australian Research Council Centre of Excellence for Coral Reef Studies, James Cook University, Townsville 4811, Queensland, Australia.

[8] Changing Ocean Research Unit, Institute for the Oceans and Fisheries, The University of British Columbia, 2202 Main Mall, Vancouver, BC, Canada V6T1Z4.

[6] Lancaster Environment Centre, Lancaster University, Lancaster, LA1 4YQ, UK.

[7] UMR 9190 MARBEC, IRD-CNRS-UM-IFREMER, Université de Montpellier, 34095 Montpellier Cedex, France.

[8] UMR ENTROPIE, Nouméa, New Caledonia.

[9] Fisheries Economics Research Unit, The University of British Columbia, 2202 Main Mall, Vancouver, BC, Canada V6T1Z4.

Abstract

Climate change can alter conditions that sustain food production and availability, with cascading consequences for human food security and global economies. Yet, food production sectors are rarely examined together, which may lead to misleading policy recommendations depending on how gains or losses in one sector are balanced by losses or gains in another. Here, we evaluate the vulnerability of societies to climate change impacts on agriculture and marine fisheries at a global-scale. Under a 'business-as-usual' scenario (RCP8.5), ~90% of the world's human population –mostly living in the most sensitive and least adaptive countries– are projected to be exposed to losses of potential food production in both sectors, while less than 3% are projected to live in regions experiencing simultaneous productivity gains by 2100. Most countries –including the most vulnerable and many of the largest CO_2 producers– would experience concomitant greater increases or smaller decreases in food production from agriculture and marine fisheries sectors under the 'strong carbon mitigation' scenario (RCP2.6). Reducing societies' vulnerability to future climate impacts requires prompt mitigation actions led by major CO_2 emitters which should be coupled with strategic adaptation within and across sectors in regions where negative impacts seem inevitable.

MAIN TEXT

Introduction

The impact of climate change on the world's ecosystems and the cascading consequences for human societies is one of the grand challenges of our time (1–3). Agriculture and marine fisheries are key food production sectors that sustain global food security, human health, economic growth, and employment worldwide (4–6), but are significantly and heterogeneously affected by climatic change (7, 8), with these impacts being projected to accelerate as greenhouse gas emissions rise (9–12). Policy decisions on mitigation and adaptation strategies require understanding, anticipating, and synthesizing these climate change impacts. Central to these decisions are assessments of: (i) the extent to which impacts in different food production sectors can be compensated, (ii) the consequences for human societies, and (iii) the potential benefits of mitigation actions. In that regard, global vulnerability assessments that consider countries' exposure of food production sectors to climate-induced changes in productivity, their socioeconomic sensitivity to impacted productivity, as well as their adaptive capacity are certainly useful to define the opportunity space for climate policy, provided that food production sectors are analyzed together.

Building on previous multi-sector assessments of exposure (13, 14) and vulnerability (*11*), our purpose is to move toward a global scale analysis of human vulnerability to climate change on two major food sectors: agriculture and marine fisheries.

We draw from the vulnerability framework developed in the Intergovernmental Panel on Climate Change (IPCC)'s (Fig. 1) to assess human vulnerability to climate change impacts on agriculture and marine fisheries for, respectively, 240 and 194 countries, states or territories (hereafter "countries"). We evaluated exposure by projecting changes in productivity of agriculture (maize, rice, soy and wheat) and marine fisheries to the end of the century relative to contemporary values under two contrasting greenhouse gas emission scenarios (exposure): a 'business-as-usual' scenario (Representative Concentration Pathway, or RCP8.5) and a strong mitigation scenario (RCP2.6). To generate a comprehensive index of vulnerability for agriculture and marine fisheries, we then integrated these models with socioeconomic data on countries' dependency on each sector for food, economy and employment (sensitivity), and the capacity to respond to climate impacts by mobilizing future assets (adaptive capacity) (Fig. 1; Table S1).

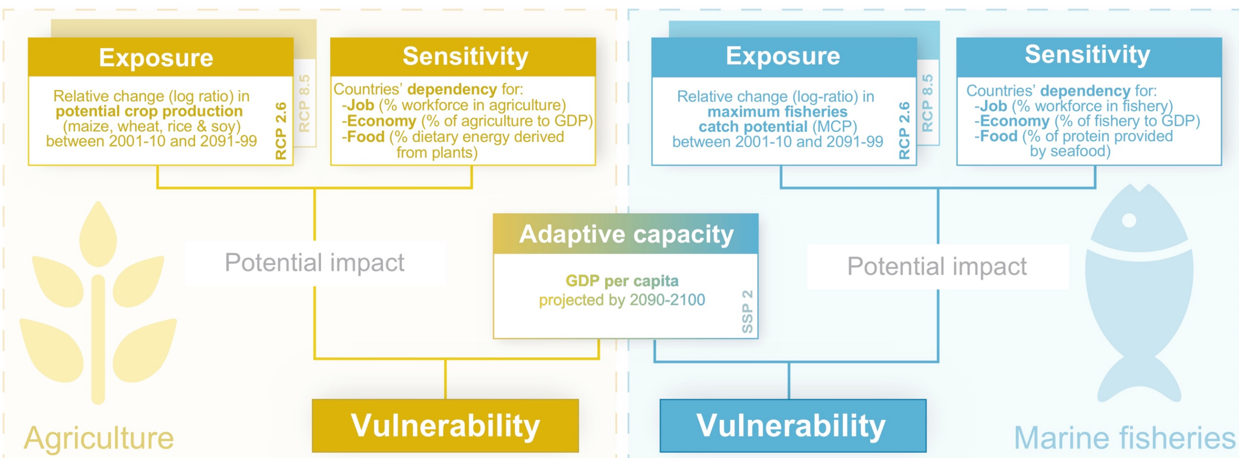

Figure 1 | IPCC vulnerability framework (AR4), adapted for our cross-sector analysis. Exposure refers here to the extent to which a food production sector is subject to a driver of change. Sensitivity refers to the strength of reliance, or dependency, on this sector in terms of employment, revenue and food security. Adaptive capacity refers to the preconditions that enable a country to mobilize resources and adjust its food system in response to climate change-induced impacts of agriculture and fisheries. Note that IPCC now bridges the AR4 definition of vulnerability with the concept of risk (AR5).

In contrast to previous global studies on vulnerability that are focused on a single sector, our approach seeks to uncover how the different vulnerability dimensions (exposure, sensitivity and adaptive capacity) of agriculture and marine fisheries interact and co-occur under future climate scenarios to derive priority areas for policy interventions and identify potential synergies or trade-offs. We examine the impacts of climate change on two global food systems sectors that are key for livelihoods and food security globally (15, 16) and for which data were available with an acceptable degree of confidence. The likely impacts on other food sectors (aquaculture, freshwater fisheries and livestock production), for which global climate change projections are less developed, are discussed only qualitatively but will be an important future research priority as climate projections on these sectors become more refined.

Results and discussion

A "perfect storm" in the tropics

Spatial heterogeneity of predicted climate change impacts on agriculture and fisheries, coupled with varying degrees of human sensitivity and adaptive capacity on these sectors, suggest that for multi-sector countries (i.e. countries engaged in both sectors, as opposed to landlocked countries with no or negligible marine fisheries), climate change may induce situations of 'win-win' (i.e. both sectors are favored by climate change), 'win-lose' (i.e. losses in one sector and gains in the other) or 'lose-lose' (i.e. both sectors are negatively impacted). Under future climate projections, tropical areas, particularly in Latin America, Central and Southern Africa and South-East Asia, would disproportionately face lose-lose situations with exposure to lower agriculture productivity and lower maximum fisheries catch potential by 2100 (Fig. 2A-B; Fig. S1). These areas are generally highly dependent on agriculture and fisheries for employment, food security, or revenue (Fig. 2C-D).

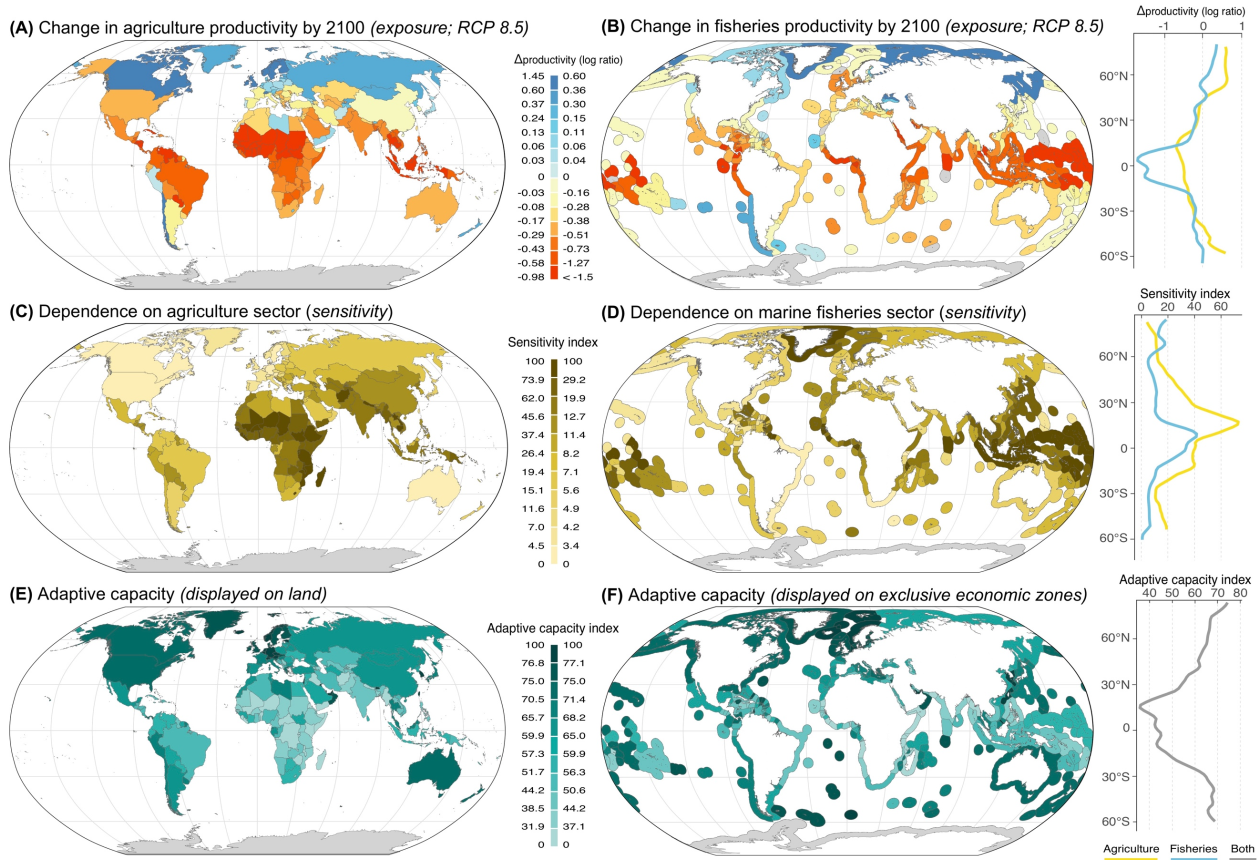

Figure 2 | Dimensions of agriculture and marine fisheries vulnerability to climate change. (A-B) Average relative changes in agriculture productivity (maize, rice, soy and wheat) and in maximum catch potential within Exclusive Economic Zones (EEZs) projected by 2100 (RCP8.5) were used to estimate exposure of agriculture and fisheries, respectively. (C-D) Sensitivity on each sector is a composite metric of dependence for food, jobs and revenue. (E-F) Adaptive capacity is based on future GDP per capita and is not sector-specific. Socioeconomic indicators (C-F) are normalized between 0 (lowest possible value) and 100 (largest possible value). The right panels are latitudinal trends. Class intervals are quantiles.

Conversely, countries situated at high latitudes (e.g. Europe, North America) –where food, jobs and revenue dependences upon domestic agriculture and seafood production are generally lower– will experience losses of lower magnitude, or even gains in some cases (e.g. Canada or Russia) under future climate conditions (Fig. 2A). This latitudinal pattern of exposure is consistent across both climate change scenarios (Fig. S1) and is mostly due to the combined effects of increased temperature, rainfall changes, water demand, and CO_2 effects on photosynthesis and transpiration (agriculture), and temperature-induced shifts in species' distribution ranges due to changes in suitable habitat and primary production (marine fisheries), as reported in other studies (*10*, *12*, *17*–*19*).

The different dimensions of vulnerability generally merge to create a "perfect tropical storm" where the most vulnerable countries to climate change impacts on agriculture are also the most vulnerable to climate impacts on their fisheries (ρ=0.67; p-value<0.001 under RCP8.5, and ρ=0.68; p-value<0.001 and RCP2.6; Fig. 3; Fig. S2). For agriculture and, to a lesser extent, fisheries, sensitivity is negatively correlated with adaptive capacity (ρ=-0.79; p-value<0.001 for agriculture; ρ=-0.12; p-value=0.07, respectively; Fig. S2), indicating that countries that are most dependent on food production sectors generally have the lowest adaptive capacity (Fig. 2). The potential impacts (i.e. the combination of exposure and sensitivity) of climate change on agriculture or fisheries will be exacerbated in the tropics, where most developing countries with lower capacity to respond to and recover from climate change impacts are located. Overall, vulnerability remains consistent across scenarios, with countries most vulnerable under RCP8.5 also ranking high under RCP2.6 for both sectors, and vice-versa (ρ= 0.98; p-value<0.001 and ρ= 0.96; p-value<0.001 for agriculture and fisheries vulnerability, respectively).

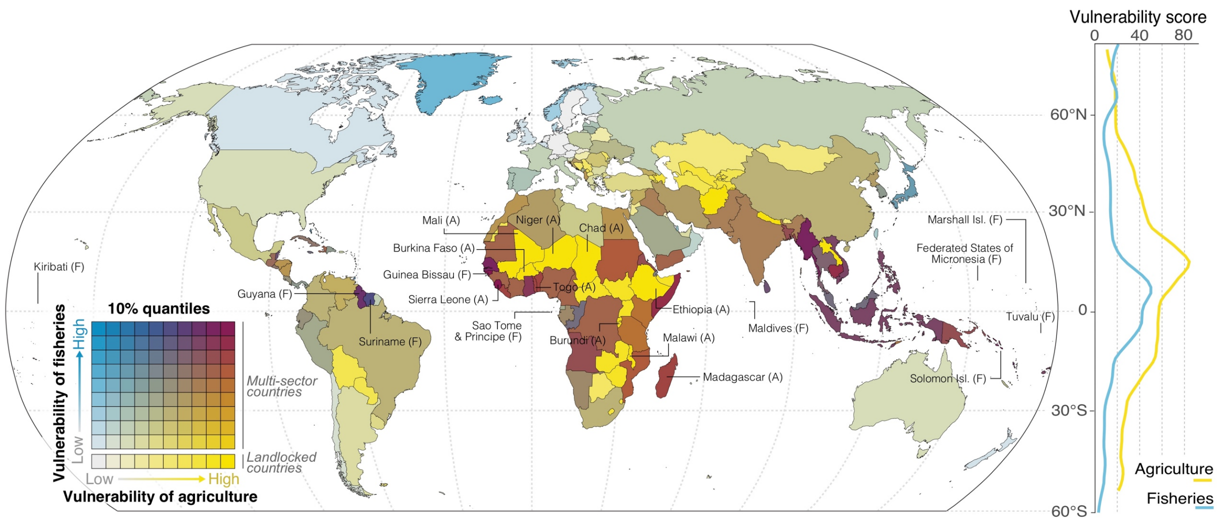

Figure 3 | Vulnerability of agriculture and marine fisheries as a function of exposure, sensitivity and adaptive capacity to the impacts of climate change. The bivariate map shows linked vulnerabilities of agriculture and fisheries for each country under RCP8.5. The 10 most vulnerable countries are indicated for agriculture (A) and marine fisheries (F). Right panel indicates latitudinal trends.

Challenges and opportunities for sectorial adaptation

The most vulnerable countries will require transformative changes focusing on adjusting practices, processes, and capital within and across sectors. For example, within-sector strategies such as diversification towards crops with good nutritional value can improve productivity and food security if they match with the future climate conditions (20).

Although many opportunities for strategic crop diversification seem to be available under RCP2.6, few options would remain under RCP8.5 (Figs. S3-4).

In some cases, cross-sector adaptation may be an option by diversifying away from negatively impacted sectors and into positively impacted ones (i.e. moving out of the loss and into the win sector in win-lose conditions). For example, some countries projected to experience losses in fisheries productivity by 2100 would experience gains in agriculture productivity (Fig. 4; Fig. S1), indicating potential opportunities for national-scale reconfiguration of food production systems. By contrast, few countries are projected to experience gains in fisheries and losses in agriculture (n=28 under RCP2.6, n=14 under RCP8.5; Fig. 4).

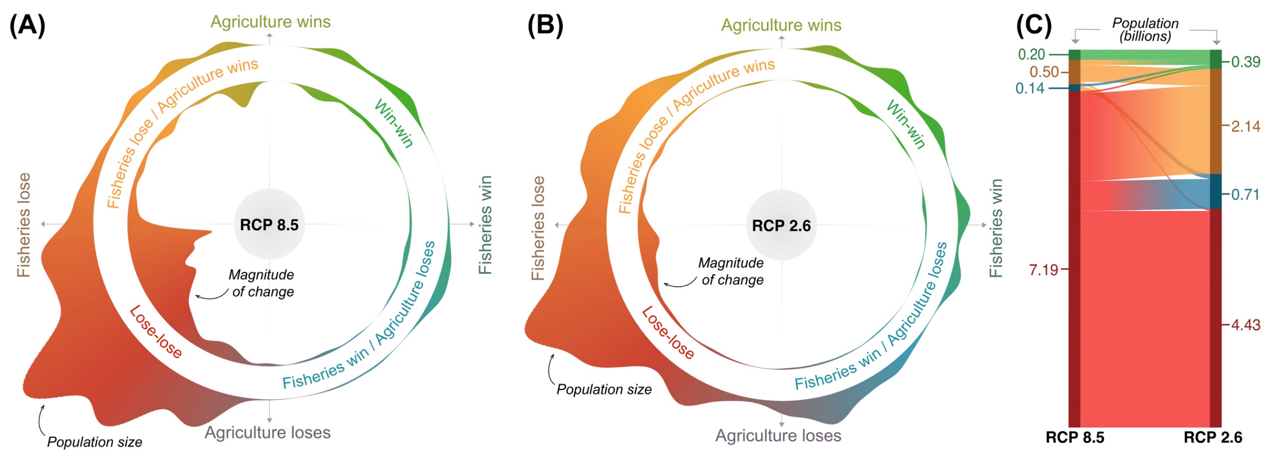

Figure 4 | Magnitude of changes in agriculture and marine fisheries productivity, and impacted population size, according to two CO_2 emissions scenarios. (A-B) Radial diagrams show projected concomitant changes in agriculture and marine fisheries productivity, where the angle describes the relative contribution of each sector to overall change (0°: gain in agriculture only; 90°: gain in fisheries only; 180°: loss in agriculture only; 270°: loss in fisheries only) and thus describe win-win (green), lose-lose (red) and win-lose (yellow and blue) exposure categories. Each diagram consists of two rings. The inner ring represents the overall magnitude of the projected changes, measured as the distance between each country's projected change and the origin (i.e. no change) in an orthogonal coordinate system. The outer ring indicates human population projected to be living at each bearing by 2100. (C) Alluvial diagram illustrates how the total number of people projected to experience win-win (green), win-lose (blue and orange) and lose-lose (red) situations varies according to the emission scenario. Numbers are in billions (summations may not be exact owing to rounding) and only account for the projected population by 2100. See Fig. S1 for global maps of each exposure category and Fig. S5 for model uncertainty surrounding these estimates.

Opportunities for cross-sector diversification may be constrained not only by climate change policy (see "Reducing exposure through climate mitigation") but also by poor environmental governance. Indeed, any identified potential gains in productivity are under the assumption of good environmental management (i.e. crops and fisheries being sustainably managed). Fish stocks and crops in many tropical countries are currently unsustainably harvested (21, 22), which may constrain any potential climate-related gains and increase the global burden, unless major investments in sectorial governance and sustainable intensification are made (20, 23, 24).

Reducing exposure through climate mitigation

Vulnerability of both agriculture and fisheries to climate change can be greatly reduced if measures to mitigate greenhouse gas emissions are taken rapidly. Under a 'business-as-usual' emission scenario (RCP8.5), almost the entire world's human population (~97%) is projected to be directly exposed to high levels of change in at least one food production sector by 2100 (outer ring in Fig. 4A; Fig. S1). Additionally, 7.2 billion people (~90% of the world's future population) would live in countries projected to be exposed to lose-lose conditions (i.e. productivity losses in both sectors). These countries generally have high sensitivity and weak adaptive capacity (Fig. S1). In contrast, only 0.2 billion people (<3% of the world's projected population) would live in regions projected to experience a win-win situation under RCP8.5 (i.e. productivity gains in both sectors) by the end of this century (outer ring in Fig. 4B; Fig. S1). Under a 'strong carbon mitigation' scenario (i.e. RCP2.6), however, lose-lose situations would be reduced by a third, so ~60% of the world's population, while win-win situations would increase by a third so up to 5% of the world's population, mostly because of improved agricultural productivity (Fig. 4).

Although losses in productivity potential would be inevitable in many cases, the magnitude of these losses would be considerably lower under RCP2.6, notably for countries facing lose-lose conditions whose average change in productivity would move from about -25% to -5% for agriculture and from -60% to -15% for fisheries (see change in inner rings in Fig. 4A-B). Main improvements would occur in Africa (all crops and marine fisheries), Asia (mostly marine fisheries and wheat), and South America (mostly wheat and soy) but also in Europe (mostly marine fisheries) and North America (mostly wheat and marine fisheries; Fig S6). Hence, although negative consequences of climate change cannot be fully avoided in some regions of the world such as Africa, Asia and Oceania, they have the potential to be drastically lowered if mitigation actions are taken rapidly.

Pathways for reducing exposure to the impacts of climate change through reduced greenhouse gas emissions should include global action and be long-lasting to achieve the Paris Agreement targets (a pathway similar to RCP2.6) which can massively reduce human vulnerability to climate change impact on food production systems. Overwhelmingly, net gains (i.e. higher gains, lower losses or losses to gains) from a successful climate mitigation strategy would prevail over net losses (i.e. higher losses, lower gains or gains to losses) (Fig. 5A). Most vulnerable countries, in particular, would experience the highest net productivity gains (mostly through lower losses), while least vulnerable countries would benefit less from emission reductions as they would generally experience lower net productivity gains, and in some cases net productivity losses (Fig. 5A; Fig. S7).

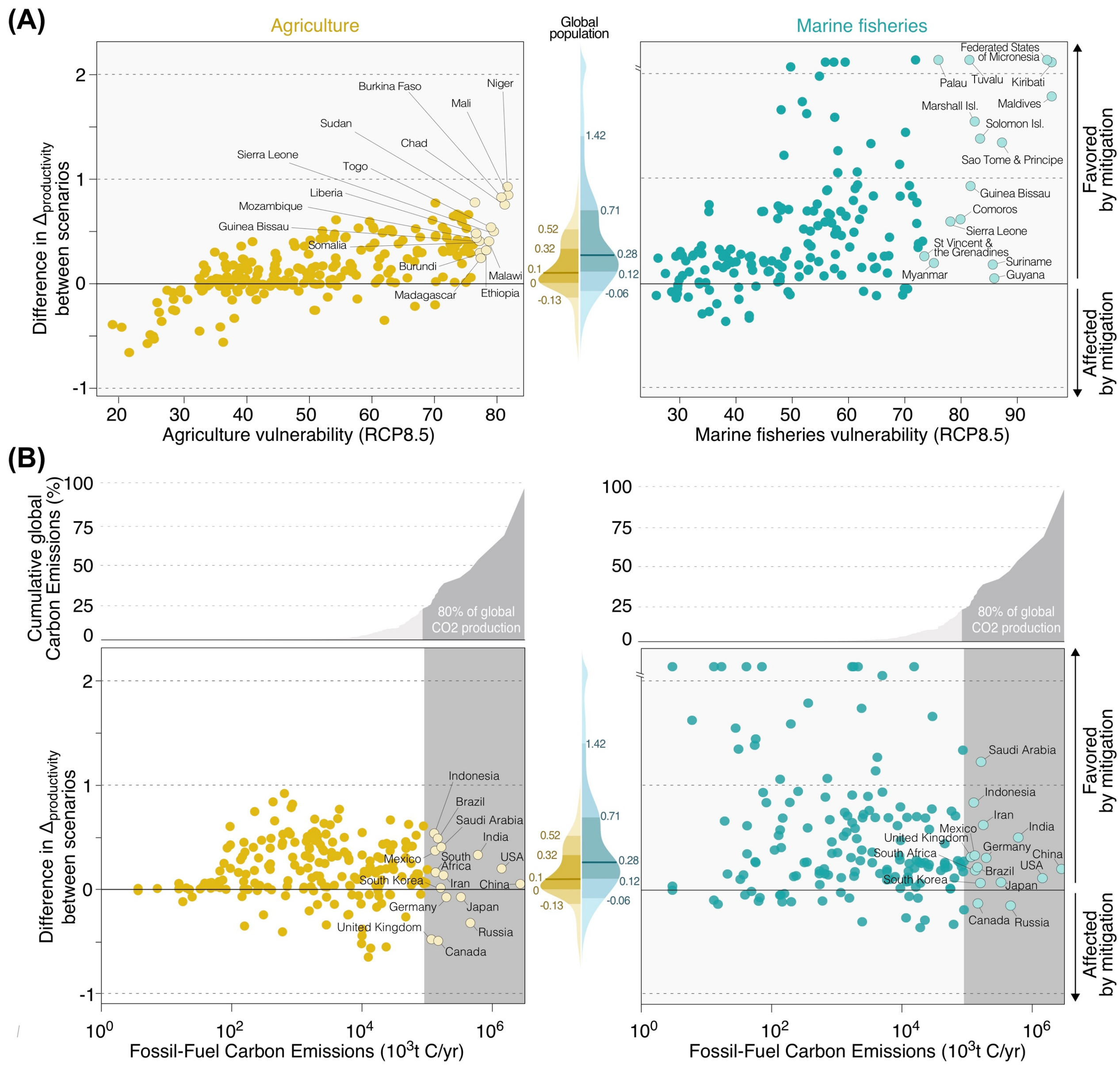

Figure 5 | Climate mitigation benefits for agriculture and marine fisheries productivity at the country-level. (A) Countries' net change in future agriculture and fisheries productivity potential induced by climate mitigation plotted against their corresponding vulnerability under RCP8.5**.** Net change represents the projected differences in changes in productivity potential from RCP8.5 (business-as-usual) to RCP2.6 (highly successful reduction of greenhouse gas emissions); negative and positive values thus indicate net loss (i.e. lower gains, higher losses, or gains-to-losses) and net gain (i.e. higher gains, lower losses, or losses-to-gains) from climate mitigation, respectively. The 15 most vulnerable countries are indicated. (B) Countries' net change in future agriculture and fisheries productivity potential plotted against annual CO_2 production with the top 15 CO_2 producers indicated. Density plots show the distribution of the world's population, and values report net change in sectors' productivity at the 10^{th}, 25^{th}, 50^{th} and 90^{th} percentiles of the distribution. See Fig. S7 for global estimates on mitigation benefits and Table S2 for details on the most vulnerable countries and top CO_2 producers.

Although this may appear as a bleak outlook for global climate mitigation, we show that among the 15 countries currently contributing to ~80% of the global greenhouse gas production, most would experience net productivity gains (lower losses or losses to gains) in agriculture (n=10) and fisheries (n=13) from moving from RCP8.5 to RCP2.6. These include countries with large per capita emissions such as USA, China and Saudi Arabia. Conversely, countries projected to experience mitigation-induced net losses in productivity would do so via lower gains, regardless of the sector considered (Fig. 5B; Table S2). These results strongly suggest that committing to reduced emissions can dramatically reduce the burden of climate change, in particular on the most vulnerable regions, while benefitting agricultural and fisheries sectors of most of the largest CO_2 producers, thus providing additional incentives for advancing the climate mitigation agenda.

Caveats and future directions

Although we present a new, integrated vision on the challenges faced by two globally significant food production sectors, many gaps of knowledge remain. First, the above estimates of people experiencing win-win, win-lose or lose-lose situations are rough estimates given the uncertainties inherent to the climate impact models that are used to estimate exposure ((*10*, *12*); Fig. S5). In addition, long-term trends in productivity changes overlook extreme or 'black swan' events (e.g. pest and diseases, extreme weather, political crises, etc.) that can play a critical role in food (in)stability and therefore food security (*25*). Although these caveats may weaken the robustness of the conclusions (*26*), they should not hinder action at this point, as the results remain broadly similar to other assessments that used different modelling approaches, assumptions and data (*17–19*).

Second, our metric of agriculture exposure adds together various globally significant crops out of which a significant proportion (36%) is used to feed animals (*27*). While projections for other crops such as ground nuts, roots, peas and other cereals suggest similar geographical patterns of change (Fig. S4 and Fig. S8), on changes for other locally and/or nutritionally significant crops (*28*) (e.g. fruits, legumes, etc.) remain largely unknown, highlighting an important area for future model development.

Third, each vulnerability dimension interacts with global forces that remain largely unpredictable. These include how governments will prioritize these sectors in the future, changes in trade policies, shifting dietary preferences, changes in technologies, advances in gene editing techniques increasing crop yields, and changes in arable land and cropping density due to the interactions between arable land extension, production intensification, and soil erosion and degradation eliminating areas for cultivation, among others. Together, these gaps provide a strong motivation for more detailed integration of insights from several disciplines (*29*, *30*).

Fourth, while we decided to limit the scope of our analysis to food production sectors for which global climate change projections were well developed, it is worth noting that different patterns of vulnerability may emerge if different sectors were included. Considering freshwater fisheries, for instance, would provide valuable insights into new opportunities (or challenges) in vulnerable countries that have a significant inland fishery sector (e.g. Malawi, Sierra Leone, Uganda, Guyana or Bangladesh). The evidence so far seems to suggest that there is not much potential for increased inland fisheries productivity due to increased competition for waters and the current high proportion (90 %) of inland catch coming from already stressed systems (*31*). Low-value freshwater species cultured domestically –an important component of food security globally and in many food-insecure regions (in particular in East and Southeast Asia; (*32*))– may be subject to the same constraints. The global potential of marine aquaculture production that does not rely on inputs from wild capture feeds (i.e. shellfish) is expected to decline under climate change, although regions such as Southeast Asia may become more suitable in the future (Fig. S9; (*33*)). For the livestock sector, decline in pasture productivity in many regions with significant broad care grazing industry (e.g. Australia, South America; see relative changes in managed grass in Fig. S4) combined with additional stresses (e.g. stock heat and water stress low-latitude regions, pests and rainfall events) is likely to outweigh potential benefits, while disruption of major feed crops (e.g. maize, Fig. S3) and marine fish stocks (Fig. 2B) used for fishmeal would affect the intensive livestock industries (*34*). Overall, climate change impacts on other food production sectors indicate the potential for further negative impacts on global food systems, although analyses that integrations among sectors are still nascent and sorely needed (*35*, *36*).

Conclusion

The goal of this analysis has been to consider the many dimensions of multi-sector vulnerability in order to inform a transition toward more integrated climate policy. On the basis of our approach and models, we conclude that although lose-lose situations will be pervasive and profound, affecting several billion people in the most food-insecure regions, climate action can dramatically minimize future impacts and benefit the overwhelming majority of the world's population. We have shown that climate action can benefit both the most vulnerable countries but also large greenhouse gas emitters to provide substantial incentives to collectively reduce global CO_2 emissions. The future will nevertheless entail societal adaptation, which could include adjustments within and across food production sectors.

Materials and Methods

Overview

Each vulnerability dimension (exposure, sensitivity and adaptive capacity) was evaluated using a set of quantitative indicators at the country-level. Exposure was projected to the end of the century (2090-2099) using two emission scenarios (RCP2.6 and RCP8.5), which provided insights into exposure levels in the case of highly successful reduction of greenhouse gas emissions (RCP2.6) and a continued business-as-usual scenario (RCP8.5). We also accounted for future development trends by incorporating GDP per capita (an indicator of adaptive capacity) projected for 2090-2100 under a "middle of the road" scenario in which social, economic, and technological trends do not shift markedly from historical patterns (SSP2). Projections were unfortunately not available for other indicators. Hence, we use multiple present-day indicators in order to capture important aspects of the *sensitivity* dimension. This works under the assumption that no major turnover would occur in the rankings (e.g. most dependent countries at present remain the most dependent in 2100), which is reasonable considering historical trends (Fig. S10). Table S1 summarizes sources and coverage of data for each indicator. In the sections bellow, we describe each dimension and their underlying indicators but do not elaborate methods as they are fully described in each data source.

Agriculture exposure

To assess exposure of countries' agricultural sector to climate change, we used yield projections from Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) Fast Track experiment dataset of global gridded crop models (GGCM) simulations (*37*). We considered relative yield changes across four major rainfed crop types (maize, rice, soy and wheat) between two 10-year periods: 2001-2010 and 2090-2099**.** Outputs from five global 0.5° resolution crop models (EPIC, GEPIC, pDSSAT, IMAGE and PEGASUS) based on five general circulation models (GCM; GFDL-ESM2M, HadGEM2-ES, IPSL-CM5ALR, MIROC-ESM-CHEM and NorESM1-M) were used. Models assume that soil quality, depth, and hydraulic properties are sufficient for sustained agricultural production. Crop models are described in full detail in (*12*). Model uncertainties are available in Fig. S5.

The methods to summarize change in agriculture productivity globally is adapted from previous work (*11*, *12*, *38*, *39*). First, we calculated each country's total productivity for each crop averaged over each period, and measured country-level relative changes as the log ratio of total productivity projected in the 2090-2099 period to baseline total productivity of 2001-2010. We repeated this process for every pair of crop model-GCM, with and without CO_2 fertilization effects, for both RCPs, and assumed present-day distributions of farm management and production area. All models included explicit nitrogen, temperature and water stresses on each crop, except PEGASUS for which results on rice were not available. Only experiments that were available for both RCP scenarios were included. We then obtained the median yield changes for each crop type and calculated the average yield change across the four crops to create the final relative change per country (i.e. our measure of agriculture exposure). Average yield changes for individual crops are presented in Fig. S3 along with six additional crops (cassava, millet, ground nut, sorghum, peas and managed grass) modelled according to the same process (Figs. S4)**.**

Impact of climate mitigation on agriculture (Fig. 5) was measured for each country as the difference between projected changes in agriculture productivity under RCP2.6 and projected changes in agriculture productivity under 8.5 averaged across all crops (maize, rice, soy and wheat). Positive values thus indicate that climate mitigation would benefit agriculture (greater gains, lower losses, or loss-to-gain), and negative values indicate that climate mitigation would affect agriculture (lower gains, greater losses, or gains-to-losses).

Marine fisheries exposure

To assess exposure of countries' marine fisheries sector to climate change, we used projections of a proxy of maximum sustainable yield of the fish stocks, Maximum Catch Potential (MCP), from the Dynamic Bioclimate Envelope Model (DBEM) (*40*). Contrary to other available global projections (*19*), the DBEM focuses largely on exploited marine fishes and invertebrates, which makes projections directly relevant to vulnerability assessment in relation to seafood production. MCP is dependent on changes in body size, carrying capacity of each spatial cell for fish stocks (dependent on the environmental suitability for their growths as well as primary productivity), and spatial population dynamics as a result of temperature, oxygen, salinity, advection, sea ice and net primary production. Catches from each fish stock are calculated by applying a fishing mortality needed to achieve maximum sustainable yield. The DBEM thus assumes that the environmental preferences of species can be inferred from their biogeography, and that the carrying capacity of the population is dependent on the environmental conditions in relation to the species' inferred environmental preferences. It also assumes that species' environmental preferences will not evolve in response to climate change. Finally, it does not account for inter-specific interactions. More detailed list of assumptions in DBEM are provided in (*40*). Model uncertainties are available in Fig. S5.

We considered relative MCP changes between two 10-year periods: 2001-2010 and 2090-2099 using the DBEM outputs driven by three GCM (GFDP, IPSL and MPI). We evaluated marine fisheries exposure by summing MCP across each country's Exclusive Economic Zones (EEZs) over each period, and measured country-level relative changes as the log ratio of total MCP projected in the 2090-2099 period to baseline total MCP of 2001-2010. We repeated this process for each GCM and used the average MCP change as a final relative change per country (i.e. our measure of fisheries exposure).

Impact of climate mitigation on fisheries (Fig. 5) was measured for each country as the difference between projected changes in MCP under RCP2.6 and projected changes in MCP under 8.5. Positive values thus indicate that climate mitigation will benefit fisheries (greater gains, lower losses, or loss-to-gain), and negative values indicate that climate mitigation will affect fisheries (lower gains, greater losses, or gains-to-losses).

Agriculture sensitivity

Sensitivity in the context of agriculture was assessed by combining metrics reflecting the contribution of agriculture to countries' economy (economic dependency), employment (job dependency) and food security (food dependency). We calculated the percentage of GDP contributed by agricultural revenue based on the World Bank's World Development Indicators (*41*) for our metric of economic dependency to agriculture. Employment data from FAOSTAT (*42*) was used to measure job dependency on the agricultural sector (*sensu* ISIC divisions 1-5). Since this data includes fishing, we subtracted the number of people employed in fisheries (see Fisheries sensitivity section) to calculate the percentage of the workforce employed by land-based agriculture as a metric of job dependency. Finally, we used the share of dietary energy supply derived from plants (2011-2013 average) from FAOSTAT's Suite of Food Security Indicators (*42*) to evaluate food dependency on agriculture.

Fisheries sensitivity

Similar to agriculture sensitivity, and in accordance with previous global assessment of human dependence on marine ecosystems (*43*), sensitivity in the context of fisheries was assessed by combining indicators of the country-level contribution of fisheries to the economy (economic dependency), employment (job dependency) and food security (food dependency). We obtained the percentage of GDP contributed by reported and unreported seafood landings in 2014 from the Sea Around Us project (*44*) to estimate economic dependency. We used a database of marine fisheries employment compiled by (*5*) to calculate the percentage of the workforce employed in fisheries and thus measure countries' dependency on this sector for employment. Finally, we used the food supply dataset from FAOSTAT (*42*) to compute the fraction of consumed animal protein supplied by seafood and evaluate food dependency on fisheries.

Adaptive capacity

We considered that adaptive capacity was not differentiated by sector, and thus evaluated each country's future adaptive capacity using the average per capita GDP for the years 2090-2100 using GDP and population projections (*45*). We used the intermediate development scenario for purpose of comparability between RCP scenarios. In countries where projected GDP per capita was not available (mostly small island nations), we used the gridded (0.5°) population and GDP version developed by (*46*) based on data from (*45*).

GDP per capita is a commonly used metric to estimate countries' ability to mobilize resources to adapt to climate change. GDP per capita was strongly and positively correlated with other indicators of adaptive capacity that could not be projected to 2100 including key dimensions of governance (voice and accountability, political stability and lack of violence, government effectiveness, regulatory quality, rule of law, and control of corruption) and economic flexibility (Fig. S11).

Missing data

The main data sources (Table S1) allowed estimation of vulnerability for 84.8% of the world's population. Territories and dependencies with missing data were assigned their sovereign's values, which increased the total proportion of the population represented to 98.4%. Finally, the remaining 1.6% was imputed using boosted regression trees to predict each individual indicator using all other indicators, with the exception of a few areas ($<0.1\%$ of total population) for which one indicator (agriculture exposure) was not imputed because it could not be treated as a regression problem; i.e. it depends on future climatic conditions rather than on current countries' socioeconomic and governance indicators.

Aggregated vulnerability index

In order to combine each vulnerability dimension (exposure, sensitivity and adaptive capacity) into a single, country-level metric of vulnerability per sector and per emission scenario, we first standardized all the indicators to a scale ranging from 0 to 100 using the following formula (*47*, *48*):

$$\text{Indicator}_i = 100 * \exp[\ln(0.5) * (F_i/F_{50})] \qquad \text{(Eq. 1)}$$

where F_i is the factor (e.g. % of workforce employed in fisheries, percentage of GDP contributed by agriculture, governance status) for the i^{th} unit (e.g. a country, state, or territory) under consideration, and F_{50} is the median of the full range of values for this factor across all units. When needed, indicators were reversed so that high values convey high levels of a given vulnerability dimension (e.g. highly negative changes in agriculture productivity relate to high exposure). Each normalized indicator was then aggregated into its corresponding vulnerability dimension (e.g. job, revenue and food dependency combined into a single metric of sensitivity) by averaging the standardized indicators. Finally, the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) aggregation method was employed to calculate the country-level vulnerability index:

$$V_{i,s} = d^{+}_{i,s} / (d^{+}_{i,s} + d^{-}_{i,s}) \quad * 100 \qquad \text{(Eq. 2)}$$

where $V_{i,s}$ is the composite index of vulnerability of the country i for the sector s (agriculture or marine fisheries), $d^{+}_{i,s}$ is the distance to the positive ideal solution (i.e. minimum exposure and sensitivity, and maximum adaptive capacity; A^{+}) of the i^{th} country's sector s in the Euclidean space, and $d^{-}_{i,s}$ is the distance to the negative ideal solution (i.e. maximum exposure and sensitivity, and minimum adaptive capacity; A^-) of the i^{th} country's sector *s* in the Euclidean space. The vulnerability index may range between 0 when the vulnerability dimensions correspond and A^+, to 100 when they correspond to A^-. This approach assumes that exposure, sensitivity and adaptive capacity equally determine overall vulnerability (unweighted). Given that vulnerability dimensions are highly correlated (Fig. S2), an unequal weighting scheme would have little effect on the final vulnerability metric.

Overall, our dataset covers 240 and 194 countries/states/territories for agriculture and for fisheries, respectively, thus providing the most comprehensive assessment of vulnerability to climate change impacts on agriculture and marine fisheries to date. Analyses on the interactions between agriculture and fisheries vulnerability (e.g. Fig. 3) were only performed on multi-sector countries (i.e. landlocked countries were not considered). All data analyses were performed using R.

Greenhouse gas emissions

The most up-to-date data available on countries' total amount of CO_2 emitted from the consumption of fossil-fuels (2014) were retrieved from Carbon Dioxide Information Analysis Center (*49*). The RCP2.6 is a strong mitigation greenhouse gas emissions scenario, which by the end of the 21st century is projected to lead to a net radiative forcing of 2.6 Wm^{-2}. The RCP8.5 is a high business-as-usual greenhouse gas emissions scenario that projects a net radiative forcing of 8.5 Wm^{-2} by the end of this century.

Human population estimates

Country-level projected human populations to 2090-2100 were obtained from the SSP Database 2.0 (*50*) using the intermediate shared socioeconomic pathway (SSP2) to allow comparison of population comparison between RCPs scenarios. Population projections under SSP2 assumes medium fertility, medium mortality, medium migration and the Global Education Trend (GET) education scenario for all countries. In countries where projected population was not available, we used the gridded (0.5°) population and GDP version developed by (*46*) based on data from (*45*).

H2: Supplementary Materials

Table S1: Indicators and main data sources used to measure country-level metrics of agriculture and marine fisheries vulnerability to climate change.

Table S2: Effect of strong climate mitigation on top C02 producers and on the most vulnerable countries.

Fig. S1: Spatial variation in agriculture and marine fisheries exposure, and associated levels of sensitivity and adaptive capacity according to emission scenarios RCP 2.6 and RCP 8.5.

Fig. S2: Relationships between agriculture and marine fisheries vulnerability to climate change under RCP8.5 and RCP2.6.

Fig. S3: Changes in productivity for maize, rice, soy and wheat crops under RCP2.6 and RCP8.5.

Fig. S4: Changes in productivity for six other crops under RCP2.6 and RCP8.5.

Fig. S5: Uncertainty in projected changes in agriculture and marine fisheries productivity.

Fig. S6: Regional changes in agriculture and marine fisheries productivity under RCP2.6 and RCP8.5.

Fig. S7: Net gains and losses in agriculture and fisheries productivity from climate mitigation.

Fig. S8: Spearman's rank correlations among pairs of agricultural crops changes in productivity under RCP2.6 and RCP8.5.

Fig. S9: Projected changes in finfish and bivalve aquaculture production potential under climate change.

Fig. S10: Correlations between historical and present-day indicators of sensitivity.

Fig. S11: Spearman's rank correlations among pairs of adaptive capacity indicators.

References and Notes

1. S. J. Vermeulen, B. M. Campbell, J. S. I. Ingram, Climate Change and Food Systems. *Annu. Rev. Environ. Resour.* **37**, 195–222 (2012).

2. M. R. Smith, S. S. Myers, Impact of anthropogenic CO2 emissions on global human nutrition. *Nat. Clim. Chang.* **8** (2018), doi:10.1038/s41558-018-0253-3.

3. C. Mora *et al.*, Broad threat to humanity from cumulative climate hazards intensified by greenhouse gas emissions. *Nat. Clim. Chang.* (2018), doi:10.1038/s41558-018-0315-6.

4. FAO, *The future of food and agriculture: Trends and challenges* (2017; http://www.fao.org/publications/card/en/c/d24d2507-41d9-4ec2-a3f8-88a489bfe1ad/).

5. L. C. L. Teh, U. R. Sumaila, Contribution of marine fisheries to worldwide employment. *Fish Fish.* **14**, 77–88 (2013).

6. A. D. Dangour, G. Mace, B. Shankar, Food systems, nutrition, health and the environment. *Lancet Planet. Heal.* **1**, e8–e9 (2017).

7. D. Lobell, W. Schlenker, J. Costa-Roberts, Climate trends and global crop production since 1980. *Science (80-.).* **333**, 616–620 (2011).

8. C. M. Free *et al.*, Impacts of historical warming on marine fisheries production. *Science (80-.).* **363**, 979–983 (2019).

9. C. A. Stock *et al.*, Reconciling fisheries catch and ocean productivity. *Proc. Natl. Acad. Sci.*, 201610238 (2017).

10. W. W. L. Cheung *et al.*, Large-scale redistribution of maximum fisheries catch potential in the global ocean under climate change. *Glob. Chang. Biol.* **16**, 24–35 (2010).

11. J. L. Blanchard *et al.*, Linked sustainability challenges and trade-offs among fisheries, aquaculture and agriculture. *Nat. Ecol. Evol.* **1** (2017), doi:10.1038/s41559-017-0258-8.

12. C. Rosenzweig *et al.*, Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proc. Natl. Acad. Sci.* **111**, 3268–3273 (2014).

13. F. Piontek *et al.*, Multisectoral climate impact hotspots in a warming world. *Proc. Natl. Acad. Sci.* **111**, 3233–3238 (2014).

14. K. L. O'Brien, R. M. Leichenko, Double exposure : assessing the impacts of climate change within the context of economic globalization. *Glob. Environ. Chang.* **10**, 221–232 (2000).

15. J. Rice, S. M. Garcia, Fisheries, food security, climate change, and biodiversity: characteristics of the sector and perspectives on emerging issues. *ICES J. Mar. Sci.* **68**, 1343–1353 (2011).

16. C. Béné *et al.*, Feeding 9 billion by 2050 – Putting fish back on the menu. *Food Secur.* **7**, 261–274 (2015).

17. C. Mora *et al.*, Suitable Days for Plant Growth Disappear under Projected Climate Change: Potential Human and Biotic Vulnerability. *PLoS Biol.* **13**, e1002167 (2015).

18. C. Mora *et al.*, Biotic and Human Vulnerability to Projected Changes in Ocean Biogeochemistry over the

21st Century. *PLoS Biol.* **11** (2013), doi:10.1371/journal.pbio.1001682.

19. H. K. Lotze *et al.*, Global ensemble projections reveal trophic amplification of ocean biomass declines with climate change. *Proc. Natl. Acad. Sci.*, 201900194 (2019).
20. S. M. Howden *et al.*, Adapting agriculture to climate change. *Proc. Natl. Acad. Sci.* **104**, 19691–19696 (2007).
21. C. Costello *et al.*, Status and solutions for the world's unassessed fisheries. *Science (80-.).* **338**, 517–520 (2012).
22. J. Barlow *et al.*, The future of hyperdiverse tropical ecosystems. *Nature* (2018), doi:10.1038/s41586-018-0301-1.
23. S. D. Gaines *et al.*, Improved fisheries management could offset many negative effects of climate change. *Sci. Adv.* **4**, eaao1378 (2018).
24. Z. Cui *et al.*, Pursuing sustainable productivity with millions of smallholder farmers. *Nature* (2018), doi:10.1038/nature25785.
25. R. S. Cottrell *et al.*, Food production shocks across land and sea. *Nat. Sustain.* (2019), doi:10.1038/s41893-018-0210-1.
26. D. B. Lobell, Climate change adaptation in crop production : Beware of illusions. *Glob. Food Sec.* **3**, 72–76 (2014).
27. E. S. Cassidy, P. C. West, J. S. Gerber, J. A. Foley, Redefining agricultural yields: From tonnes to people nourished per hectare. *Environ. Res. Lett.* **8** (2013), doi:10.1088/1748-9326/8/3/034015.
28. W. Willett *et al.*, Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. *Lancet*. **393**, 447–492 (2019).
29. U. R. Sumaila *et al.*, Benefits of the Paris Agreement to ocean life, economies, and people. *Sci. Adv.* **5**, eaau3855 (2019).
30. G. C. Nelson *et al.*, Climate change effects on agriculture: Economic responses to biophysical shocks. *Proc. Natl. Acad. Sci.* **111**, 3274–3279 (2014).
31. P. B. McIntyre, C. A. Reidy Liermann, C. Revenga, Linking freshwater fishery management to global food security and biodiversity conservation. *Proc. Natl. Acad. Sci.* **113**, 12880–12885 (2016).
32. C. D. Golden *et al.*, Does Aquaculture Support the Needs of Nutritionally Vulnerable Nations? *Front. Mar. Sci.* **4**, 1–7 (2017).
33. H. E. Froehlich, R. R. Gentry, B. S. Halpern, Global change in marine aquaculture production potential under climate change. *Nat. Ecol. Evol.* **2**, 1745–1750 (2018).
34. P. K. Thornton, J. Van De Steeg, A. Notenbaert, M. Herrero, The Impacts of Climate Change on Livestock and Livestock Systems in Developing Countries : A Review of What We Know and What We Need to Know. *Agric. Syst.* **101**, 113–127 (2009).
35. R. S. Cottrell *et al.*, Considering land-sea interactions and trade-offs for food and biodiversity. *Glob. Chang.*

Biol. **24**, 580– 596 (2018).

36. B. S. Halpern *et al.*, Putting all foods on the same table: Achieving sustainable food systems requires full accounting. *Proc. Natl. Acad. Sci.* **116**, 18152–18156 (2019).

37. L. Warszawski *et al.*, The Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP): Project framework. **111**, 3228–3232 (2014).

38. C. Müller, A. Bondeau, A. Popp, K. Waha, M. Fader, in *Development and climate change* (2010).

39. T. Wheeler, J. von Braun, Climate Change Impacts on Global Food Security. *Science (80-.).* **341**, 508–513 (2013).

40. W. W. L. Cheung *et al.*, Structural uncertainty in projecting global fisheries catches under climate change. *Ecol. Modell.* **325**, 57–66 (2016).

41. The World Bank, World Development Indicators.

42. FAO, FAO Statistics. *Food Agric. Organ. United Nations* (2014), (available at http://faostat3.fao.org/home/E%5Cnhttp://faostat3.fao.org/faostat-gateway/go/to/download/Q/QC/E%5Cnhttp://faostat3.fao.org/).

43. E. R. Selig *et al.*, Mapping global human dependence on marine ecosystems. *Conserv. Lett.* **12**, e12617 (2019).

44. D. Pauly, The *Sea Around Us* Project: Documenting and Communicating Global Fisheries Impacts on Marine Ecosystems. *AMBIO A J. Hum. Environ.* **36**, 290–295 (2007).

45. R. Dellink, J. Chateau, E. Lanzi, B. Magné, Long-term economic growth projections in the Shared Socioeconomic Pathways. *Glob. Environ. Chang.* **42**, 200–214 (2017).

46. D. Murakami, Y. Yamagata, Estimation of Gridded Population and GDP Scenarios with Spatially Explicit Statistical Downscaling. *Sustainability*, 1–18 (2019).

47. D. Gustafson *et al.*, Seven Food System Metrics of Sustainable Nutrition Security. *Sustainability*. **8**, 196 (2016).

48. A. Chaudhary, D. Gustafson, A. Mathys, Multi-indicator sustainability assessment of global food systems. *Nat. Commun.* **9** (2018), doi:10.1038/s41467-018-03308-7.

49. T. a Boden, G. Marland, R. J. Andres, Global, regional, and national fossil-fuel CO2 emissions. *Carbon Dioxide Inf. Anal. Center, Oak Ridge Natl. Lab. U.S. Dep. Energy, Oak Ridge, Tenn., U.S.A.* (2014), doi:10.3334/CDIAC/00001_V2017.

50. K. Samir, L. Wolfgang, The human core of the shared socioeconomic pathways: Population scenarios by age, sex and level of education for all countries to 2100. *Glob. Environ. Chang.* **42**, 181–192 (2017).

51. R. R. Gentry *et al.*, Mapping the global potential for marine aquaculture. *Nat. Ecol. Evol.* **1** (2017), doi:10.1038/s41559-017-0257-9.

52. The World Bank Group, The Worldwide Governance Indicators (WGI) project. *Worldbank* (2015), , doi:10.1300/J109v03n04_05.

53. IMF, “Export Diversification and Quality Databases” (2014).

54. O. Cadot, C. Carrère, V. Strauss-Kahn, Trade diversification, income, and growth: What do we know? *J. Econ. Surv.* **27**, 790–812 (2013).

Acknowledgements: We thank Agence Nationale de la Recherche (ANR-14-CE03-0001-01) for financial support. JEC is supported by the Australian Research Council (CE140100020, FT160100047), the Pew Charitable Trust, the Paul M. Angell Family Foundation, and the WorldFish FISH CRP project. We also thank four anonymous reviewers for providing constructive comments on earlier versions of the manuscript. **Author contributions:** L.T, C.M and J.C designed the initial study. L.T., C.M. and J.C. developed the research and methodology, with critical input and insight from J.E.C., N.A.J.G, F.A.J-H and D.M.. L.T performed the analyses and produced the figures. W.W.C processed the fisheries exposure data and U.R.S. processed the fisheries sensitivity data. All authors interpreted the results and implications. L.T drafted the manuscript with significant input and revisions from all authors. **Competing interests:** The authors declare that they have no competing interests. **Data and material availability:** All data needed to evaluate the conclusions of the paper are available from publicly available databases. Additional data related to this paper may be requested from the authors.