

ENVIRONMENTAL STUDIES

Escaping the perfect storm of simultaneous climate change impacts on agriculture and marine fisheries

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Climate change can alter conditions that sustain food production and availability, with cascading consequences for food security and global economies. Here, we evaluate the vulnerability of societies to the simultaneous impacts of climate change on agriculture and marine fisheries at a global scale. Under a “business-as-usual” emission scenario, ~90% of the world’s population—most of whom live in the most sensitive and least developed countries—are projected to be exposed to losses of food production in both sectors, while less than 3% would live in regions experiencing simultaneous productivity gains by 2100. Under a strong mitigation scenario comparable to achieving the Paris Agreement, most countries—including the most vulnerable and many of the largest CO₂ producers—would experience concomitant net gains in agriculture and fisheries production. Reducing societies’ vulnerability to future climate impacts requires prompt mitigation actions led by major CO₂ emitters coupled with strategic adaptation within and across sectors.

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 substantially 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 affected 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 multisector 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) (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 8.5 (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 and table S1).

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 production 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 multisector 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 affected. Under future climate projections, tropical areas, particularly in Latin America, Central and Southern Africa, and Southeast Asia, would disproportionately

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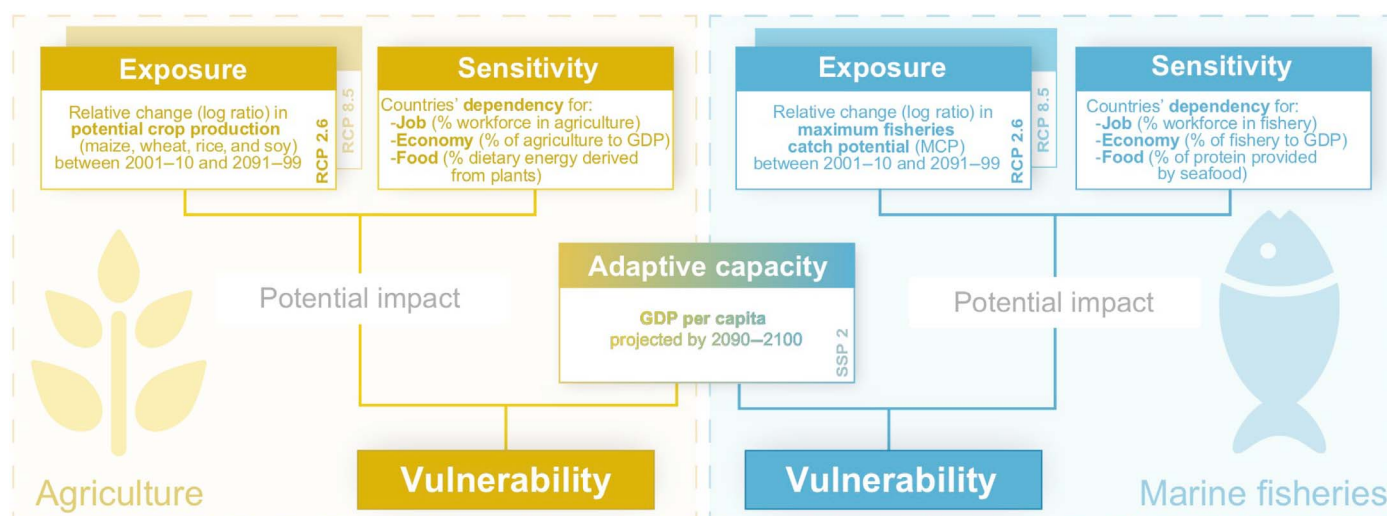


Fig. 1. IPCC vulnerability framework (AR4), adapted for our cross-sector analysis. Exposure refers here to the extent to which a food production sector is subject to a driver of change. Sensitivity refers to the strength of reliance, or dependency, on this sector in terms of employment, revenue, and 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).

face lose-lose situations with exposure to lower agriculture productivity and lower maximum fisheries catch potential by 2100 (Fig. 2, A and B, and fig. S1). These areas are generally highly dependent on agriculture and fisheries for employment, food security, or revenue (Fig. 2, C and D).

Conversely, countries situated at high latitudes (e.g., Europe and North America)—where food, jobs, and revenue dependences on 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 CO₂ effects on photosynthesis and transpiration (agriculture), as well as 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 ($\rho = 0.67$, $P < 0.001$ under RCP8.5 and $\rho = 0.68$, $P < 0.001$ under RCP2.6; Fig. 3 and fig. S2). For agriculture and, to a lesser extent, fisheries, sensitivity is negatively correlated with adaptive capacity ($\rho = -0.79$, $P < 0.001$ for agriculture and $\rho = -0.12$, $P = 0.07$ for fisheries; 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 ($\rho = 0.98$, $P < 0.001$ and $\rho = 0.96$, $P < 0.001$ for agriculture and fisheries vulnerability, respectively).

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 toward 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 and S4).

In some cases, cross-sector adaptation may be an option by diversifying away from negatively affected sectors and into positively affected 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 and 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).

Opportunities for cross-sector diversification may be constrained not only by climate change policy (see the “Reducing exposure through climate mitigation” section) but also by poor environmental governance. 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

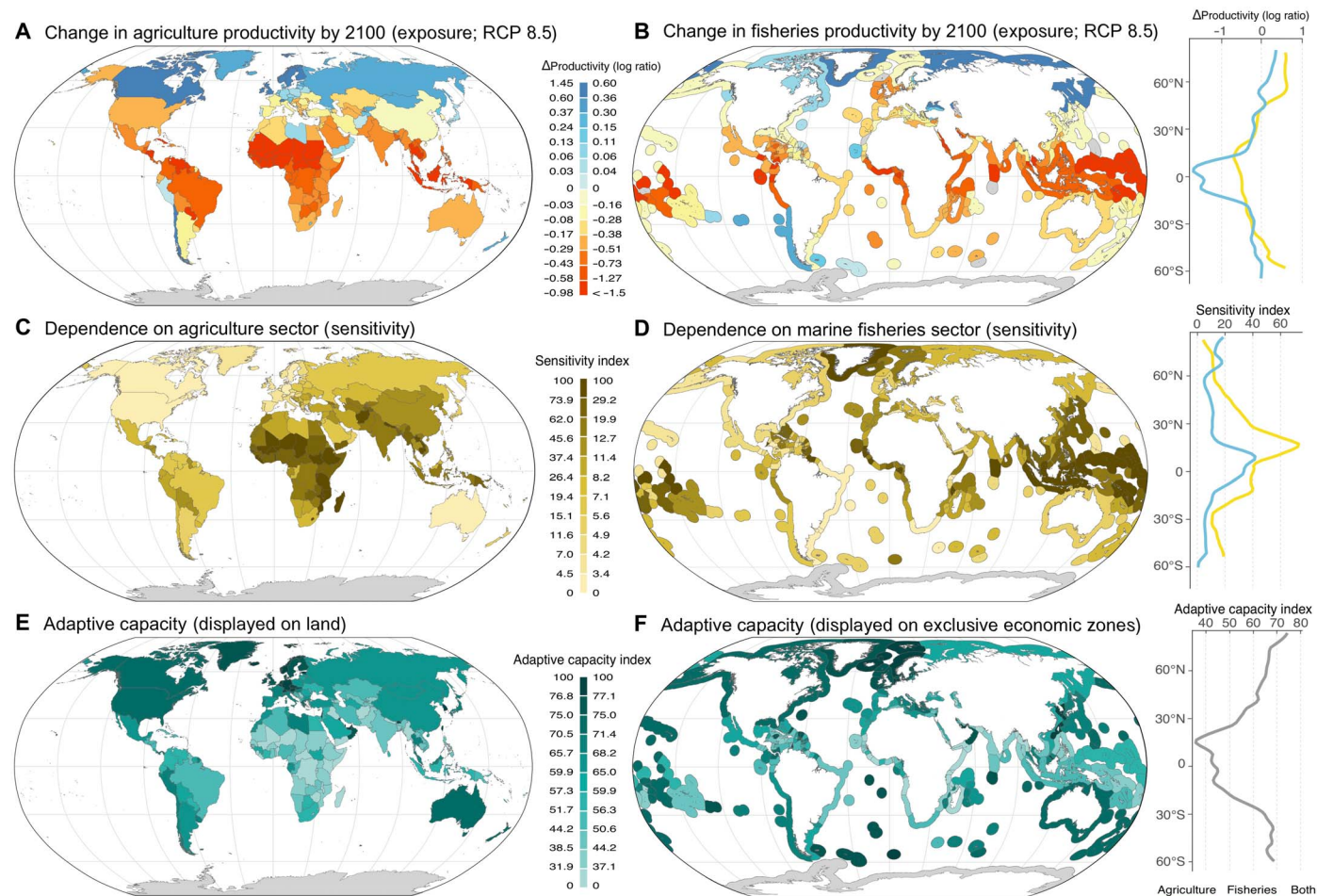


Fig. 2. Dimensions of agriculture and marine fisheries vulnerability to climate change. (A and B) Average relative changes in agriculture productivity (maize, rice, soy, and wheat) and in maximum catch potential within exclusive economic zones projected by 2100 (RCP8.5) were used to estimate exposure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

be directly exposed to high levels of change in at least one food production sector by 2100 (outer ring in Fig. 4A and 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 and 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. 4, A and 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

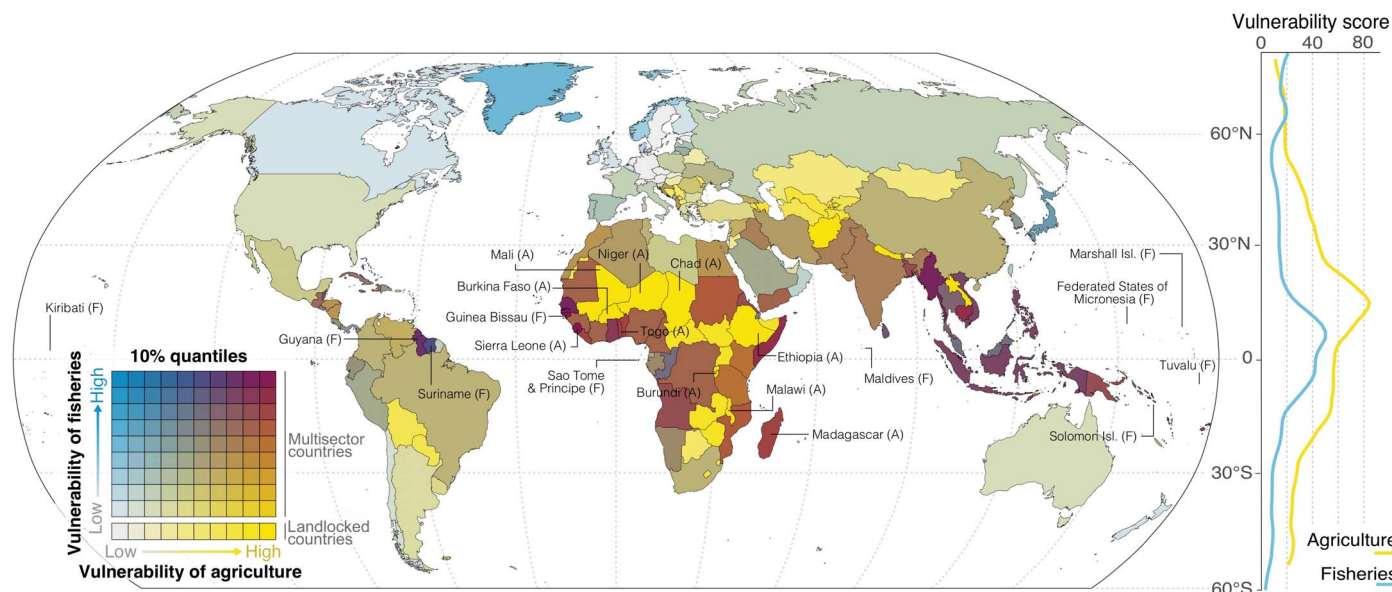


Fig. 3. Vulnerability of agriculture and marine fisheries as a function of exposure, sensitivity, and adaptive capacity to the impacts of climate change. The bivariate map shows linked vulnerabilities of agriculture and fisheries for each country under RCP8.5. The 10 most vulnerable countries are indicated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

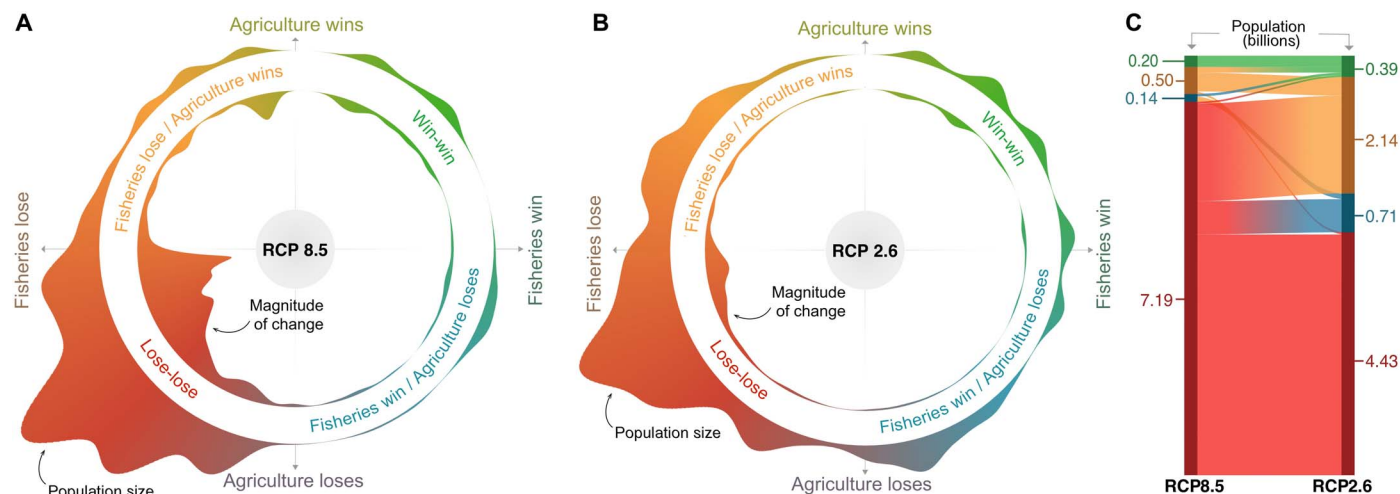


Fig. 4. Magnitude of changes in agriculture and marine fisheries productivity and affected population size, according to two CO₂ emission scenarios. (A and B) Radial diagrams show projected concomitant changes in agriculture and marine fisheries productivity, where the angle describes the relative contribution 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 describes win-win (green), lose-lose (red), and win-lose (orange 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.

generally experience lower net productivity gains and, in some cases, net productivity losses (Fig. 5A and fig. S7).

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 the United States, 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 and table S2). These results strongly suggest that committing to reduced emissions can markedly reduce the burden of climate change, in particular on the most vulnerable regions, while benefitting agricultural and fisheries

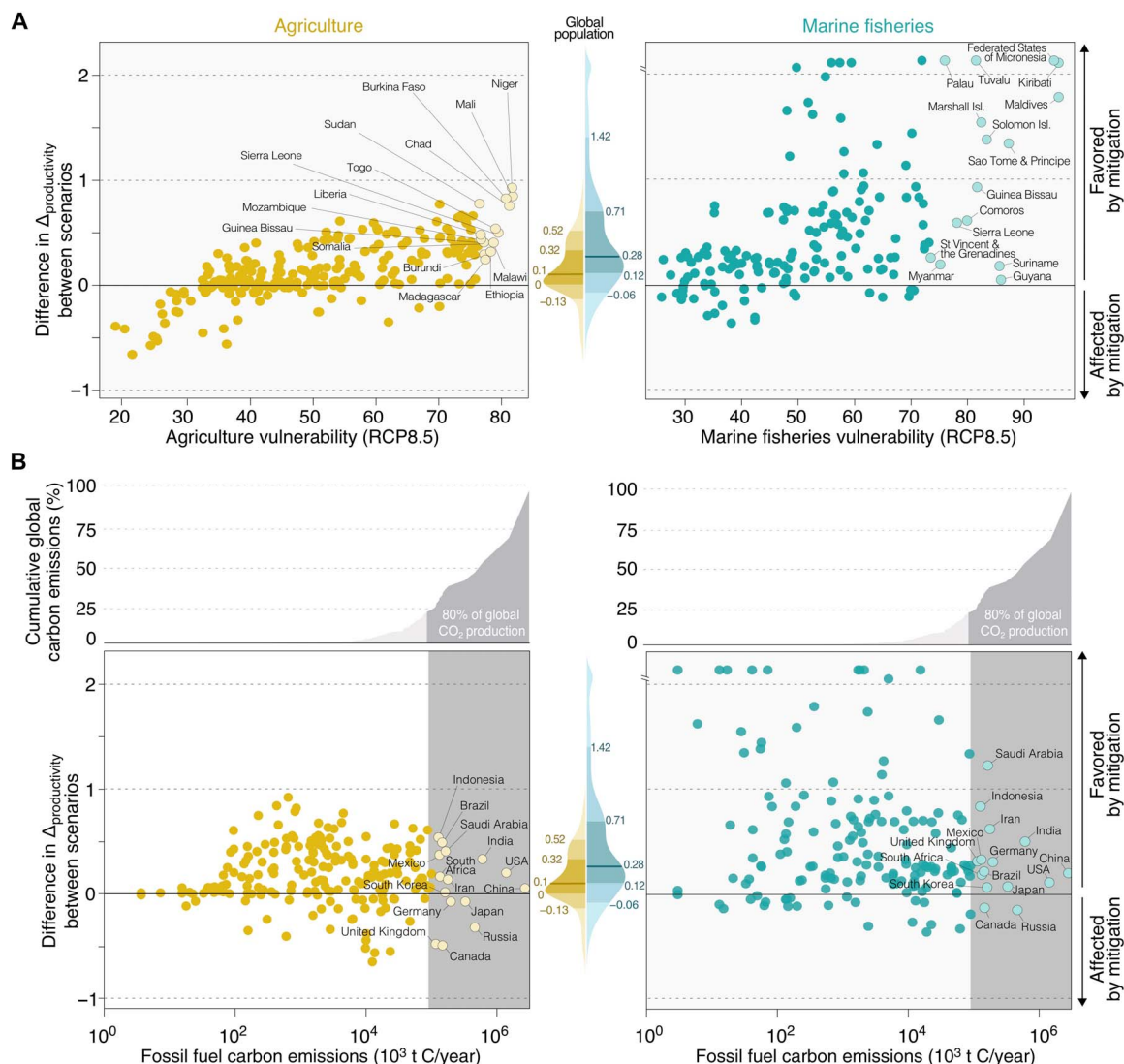


Fig. 5. Climate mitigation benefits for agriculture and marine fisheries productivity at the country-level. (A) Countries' net change in future agriculture and fisheries productivity potential induced by climate mitigation plotted against their corresponding vulnerability under RCP8.5. Net change represents 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 CO₂ production with the top 15 CO₂ producers indicated. Density plots show the distribution of the world's population, and values report net change in sectors' productivity at the 10th, 25th, 50th, and 90th 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 CO₂ producers.

sectors of most of the largest CO₂ 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 important 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, and political crises) 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 modeling approaches, assumptions, and data (17–19).

Second, our metric of agriculture exposure adds together various globally important crops, out of which a substantial 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 (figs. S4 and S8), changes for other locally and/or nutritionally important crops (e.g., fruits and legumes) (28) 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 notable 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 because of 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 notable broad-care grazing industry (e.g., Australia and 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 the global food system, but analyses that integrate multiple sectors are still nascent and sorely needed (35, 36).

CONCLUSION

The goal of this analysis has been to consider the many dimensions of multisector vulnerability 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 markedly 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 and large greenhouse gas emitters to provide substantial incentives to collectively reduce global CO₂ 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 gross domestic product (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 Shared Socioeconomic Pathway 2 (SSP2). Projections were unfortunately not available for other indicators. Hence, we used multiple present-day indicators 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 below, 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 an Inter-Sectoral Impact Model Inter-comparison (ISI-MIP) Project Fast Track experiment dataset of global gridded crop model 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 (GCMs; GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A LR, 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 were 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 CO₂ 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) modeled according to the same process (fig. S4).

The 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. Last, it does not account for inter-specific interactions. A more detailed list of assumptions in DBEM is 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 GCMs (GFDP, IPSL, and MPI). We evaluated marine fisheries exposure by summing MCP across each country's exclusive economic zones 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).

The 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) were used to measure job dependency on the agricultural sector (sensu International Standard Industrial Classification divisions 1 to 5). Since these data include fishing, we subtracted the number of people employed in fisheries (see the "Fisheries sensitivity" section) to calculate the percentage of the workforce employed by land-based agriculture as a metric of job dependency. Last, 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 in (5) to calculate the percentage of the workforce employed in fisheries and thus measure countries' dependency on this sector for employment. Last, 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 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 the 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 in (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. Current 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%. Last, 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

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)

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

where F_i is the factor (e.g., % of workforce employed in fisheries, percentage of GDP contributed by agriculture, and 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. Last, the TOPSIS (Technique for Order Preference by Similarity to an Ideal Solution) aggregation method was used to calculate the country-level vulnerability index

$$V_{i,s} = d_{i,s}^+ / (d_{i,s}^+ + d_{i,s}^-) * 100 \quad (2)$$

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 from 0, when the vulnerability dimensions correspond to 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 multisector 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 CO₂ emitted from the consumption of fossil fuels (2014) were retrieved from Carbon Dioxide Information Analysis Center (49). RCP2.6 is a strong mitigation greenhouse gas emission scenario, which, by the end of the 21st century, is projected to lead to a net radiative forcing of 2.6 W m⁻². RCP8.5 is a high business-as-usual greenhouse gas emission scenario that projects a net radiative forcing of 8.5 W m⁻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 RCP scenarios. Population projections under SSP2 assume 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 in (46) based on data from (45).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at <http://advances.sciencemag.org/cgi/content/full/5/11/eaaw9976/DC1>

Fig. S1. Spatial variation in agriculture and marine fisheries exposure, and associated levels of sensitivity and adaptive capacity according to emission scenarios RCP2.6 and RCP8.5.

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 crop 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.

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 CO₂ producers and on the most vulnerable countries.

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