WELFARE ECONOMICS

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The impact of high-end climate change on agricultural welfare

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Climate change threatens agricultural productivity worldwide, resulting in higher food prices. Associated economic gains and losses differ not only by region but also between producers and consumers and are affected by market dynamics. On the basis of an impact modeling chain, starting with 19 different climate projections that drive plant biophysical process simulations and ending with agro-economic decisions, this analysis focuses on distributional effects of high-end climate change impacts across geographic regions and across economic agents. By estimating the changes in surpluses of consumers and producers, we find that climate change can have detrimental impacts on global agricultural welfare, especially after 2050, because losses in consumer surplus generally outweigh gains in producer surplus. Damage in agriculture may reach the annual loss of 0.3% of future total gross domestic product at the end of the century globally, assuming further opening of trade in agricultural products, which typically leads to interregional production shifts to higher latitudes. Those estimated global losses could increase substantially if international trade is more restricted. If beneficial effects of atmospheric carbon dioxide fertilization can be realized in agricultural production, much of the damage could be avoided. Although trade policy reforms toward further liberalization help alleviate climate change impacts, additional compensation mechanisms for associated environmental and development concerns have to be considered.

INTRODUCTION

Climate change and rising global mean temperature (GMT) with associated consequences pose a serious threat to natural systems and socioeconomic well-being (*1*). The agricultural sector in particular is very sensitive to climate change (*2*). Even a small increase of 1° to 2°C in GMT can have significant negative effects on crop yields, especially in the tropics (*3*–*5*). In many developing regions, agriculture is of major importance for national economic performance, for example, as expressed by its share in gross domestic product (GDP) (*6*, *7*). Global economic losses in production of three major crops (wheat, maize, and barley) attributed to climate change in the recent past are estimated at approximately US$5 billion per year (*8*). With prospects of continued global warming, the implications of this damage could be substantial for poor regions, with its severity highly dependent on a country's future development path.

Climate change impacts on agriculture and resulting changes in production patterns and prices affect both producers and consumers, changing the profitability of agricultural production and the share of income spent on food (*9*, *10*). The distribution of climate change impacts on economic surpluses is consequently determined not only by the spatial features of climatic change and its impact on crop yields but also by the response of global land use patterns and trade, as well as the balancing of consumer and producer surplus (gains and losses). If food prices increase because of climate change impacts, households not only will have to spend more income on food consumption but also could face a risk of nutritional shortage and insufficient access to food (*11*). A better understanding of climate change effects on different economic agents, including potential adaptation options, can help implement suitable policies at the national and international level to buffer against potential impacts (*12*). Trade is seen as one of the most important adaptation options because it can account for changes in global patterns of agricultural productivity, and thus allows for reducing production cost and enhancing food security (*13*–*15*).

Here, we analyze climate change impacts on agricultural welfare on a global and regional scale, which are measured as changes in "consumer surplus" and "producer surplus." The impacts are dynamically assessed for the period from 1995 to 2095 using the agro-economic land use optimization model MAgPIE (Model of Agricultural Production and its Impacts on the Environment; see Materials and Methods and the Supplementary Materials) (*16*, *17*). Although there is a considerable amount of literature on climate impacts on crop yields (*5*, *18*), few studies have analyzed the subsequent economic welfare effects (*12*, *15*, *19*, *20*). MAgPIE is well suited to translate biophysical into economic impacts because crop yield patterns and water availability that are directly affected by climate change enter the economic model as spatially explicit biophysical constraints. The surplus concepts are standard analytical tools in welfare economics (*21*, *22*). Under agricultural welfare, we consider economic surplus from agricultural activities related only to plant cultivation and livestock production. Other agricultural subsectors, such as forestry and fishery, are not studied here. Producer surplus is equivalent to the production profit, that is, the difference between total revenues and production-associated costs (Fig. 1, A and B, red area). Consumer surplus is the difference between a consumer's willingness to pay for a certain good and the amount he or she actually pays for it at the market price (Fig. 1, A and B, blue area). Consumer behavior is fully deterministic in MAgPIE by exogenously defined demand trajectories for agricultural products (*23*), which implies an unbounded willingness of consumers to purchase at the market. In the case of a negative impact on the production side, the supply curve shifts upward (or leftward), and the equilibrium price increases to a new level, implying shifts in surpluses (Fig. 1B). Climate change–induced welfare impacts for food

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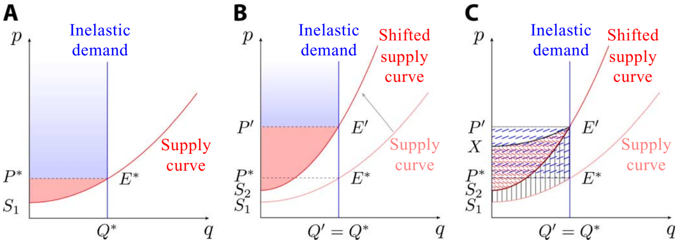

Fig. 1. Conceptual approach for welfare analysis in agricultural market. (**A**) Concept of agricultural market with one good and inelastic demand curve (as implemented in MAgPIE). The market equilibrium is established at the price P^* and the quantity Q^*. Consumer surplus is shaded in blue, and producer surplus is shaded in red. The total welfare is defined as the sum of consumer and producer surpluses. (**B**) After the shock on the supply side, the supply curve is shifted to the left, creating a new market equilibrium E' at the price P', whereas the quantity Q' equals the fixed demanded quantity Q^*, resulting in the new level of consumer and producer surpluses. (**C**) Resulting positive change in producer surplus (hatched in red, $S_2E'X$) and negative change in consumer surplus (hatched in blue, $P^*E^*E'P'$) and total welfare (hatched in gray vertical lines, $S_1E^*E'S_2$) after an upward shift of the supply curve.

producers and consumers are calculated in this analysis based on these differences in surpluses. Three indicators are considered: change in consumer surplus, change in producer surplus, and change in total agricultural welfare (the last indicator being the sum of the first two) (Fig. 1C). The economic valuation of climate change impacts in agriculture is measured by chosen indicators as a percentage change with respect to the value of future total GDP [provided by selected economic projections from the Special Report on Emissions Scenarios (SRES) (*24*)], thereby implying the effect of agricultural sector on total economic welfare. Details on economic surplus in MAgPIE are provided in the Supplementary Materials.

The market response to a climate shock is obtained through the comparison of results from a scenario with climate effect on crop yields with a reference scenario where climate conditions are fixed at the initial level in 1995. Here, we focus on high-end impacts, driving the MAgPIE model with high population growth and high greenhouse gas (GHG) emission scenario [SRES A2 (*24*)] and assuming no beneficial effects from the highly debated CO_2 fertilization (*3*, *25*, *26*) in the underlying crop yield simulations with the gridded global crop model LPJmL (Lund-Potsdam-Jena with managed Land) [figs. S1 and S2; (*27*, *28*)]. In this setting, we explore the effects of high-end climate change on agricultural welfare indicators, explicitly addressing uncertainties in patterns of climate change and the importance of trade regimes. For this, we use 19 different general circulation models (GCMs) of climate change projections that are implemented in SRES A2 and for which changes in crop yield patterns are computed, and analyze two trade regimes. Acknowledging different aspects of biophysical and socioeconomic uncertainties, we assess the sensitivity of our results to central assumptions made, including (i) the uncertainty in CO_2 fertilization, (ii) additional analyses with different crop growth models as studied by Nelson *et al.* (*29*), (iii) two alternative population and GHG emission scenarios [SRES B1 and A1B (*24*)], and (iv) agricultural demand elasticity.

To fulfill the demand for agricultural commodities under climate-impacted productivity, we endogenously estimate the most cost-effective combination of shifting the production to higher-yielding areas, including land expansion into forest and other natural vegetation area, and investments in yield-increasing technologies (research and development), which intensifies production on existing cropland. As a prominent adaptation measure, we assess the effectiveness of global trade liberalization and its adaptive potential to reduce the pressure caused by climate change on the agricultural sector. The liberalized (LIB) trade scenario in our analysis resembles current trade liberalization trends (*30*, *31*) by relaxing global trade barriers by 10% per decade. The “fixed” (FIX) trade scenario assumes that the interregional trade patterns, in terms of relative shares of regional trade flows, are fixed at levels that are the same as those in year 1995 (see the Supplementary Materials). The FIX trade scenario should not be seen as a baseline scenario because current trade is already substantially liberalized. In contrast, it should be seen as a counterfactual scenario that allows the estimation of the benefits of trade according to competitiveness. Trade regulations are included into the model in the form of regional self-sufficiency constraints. These can be interpreted as being equivalent to quotas for domestic supply, such that government revenues or spending from trade policies (for example, tariffs or subsidies) are not explicitly estimated but become part of consumer or producer rents.

RESULTS

Global climate change impacts

In both trade scenarios, climate change causes mostly positive trends in global producer surplus and negative trends in global consumer surplus toward the end of the century (Fig. 2). As a result of climate change, crop yields decrease in many areas, and producers are compelled to intensify production and/or expand cultivated areas, which leads to a rise in marginal cost of production compared to the reference scenario where no climate change occurs. As a consequence, the agricultural market responds with higher commodity prices, enabling producers to gain on average. On the other hand, consumers will have to pay more for the same basket of goods, and thus lose part of their surplus. Overall, consumers’ losses exceed producers’ benefits, creating the negative trend in agricultural welfare; this result is also consistent with other studies (*12*, *15*, *19*, *20*, *32*).

Averaged across all 19 GCM scenarios, there is a small positive climate change effect on global agricultural welfare in the beginning of the simulated period, reaching approximately 0.1% of global GDP (projected in SRES A2) in the year 2015 in the LIB and FIX trade scenario (US$34 billion and US$37 billion, respectively; table S1). Therefore, initial moderate levels of change in temperature and precipitation patterns, especially in temperate zones, can reduce the cost of agricultural production, having a positive effect on global agricultural welfare. The positive relative change is slightly stronger in the FIX scenario because it is very much constrained by fixed trade patterns, creating higher production costs, and therefore, beneficial warming would lead to a marginally bigger drop in prices compared to that in the LIB scenario (Fig. 3). As negative climate change impacts on crop yields intensify over time, the impacts on aggregate agricultural welfare become adverse after 2030, arriving at the loss of 0.3% of projected global GDP in the LIB scenario (US$884 billion) and 0.8% in the FIX scenario (US$2502 billion) in the year 2095 (table S1). Hence, in the LIB case where international trade becomes almost entirely free by the end of the century (table S2), global agricultural welfare losses in 2095 can be avoided by around 65% compared to the counterfactual scenario where trade is restricted to the 1995 pattern.

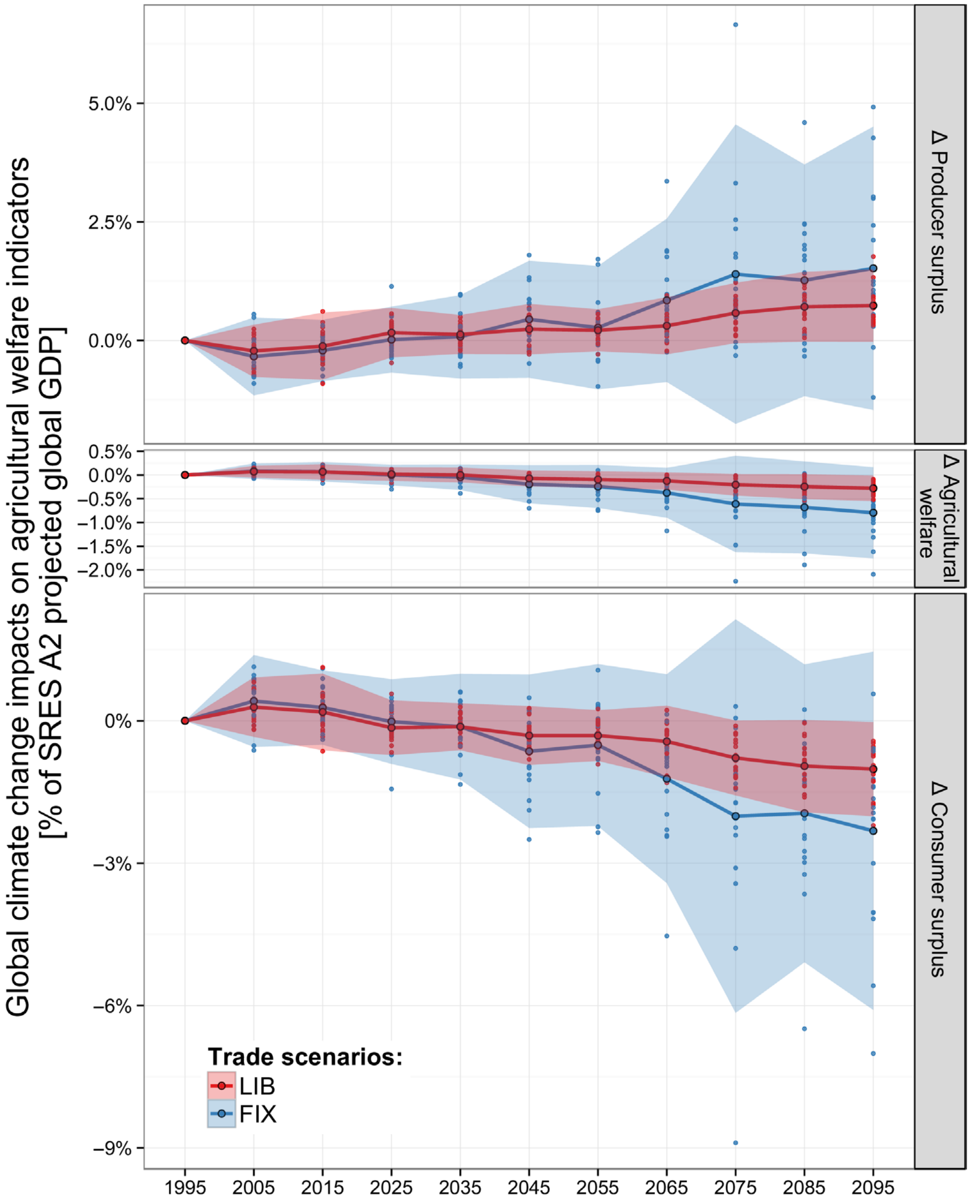

Fig. 2. Global climate change impacts on agricultural welfare indicators (% of projected global GDP in the SRES A2 scenario; without CO_2 fertilization effect). For each climate scenario (19 GCMs) used in the analysis, actual modeled changes in welfare are represented by dots, whereas solid lines for all three panels connect average values of calculated impacts for every simulated time step. Shaded areas depict double SD from the mean.

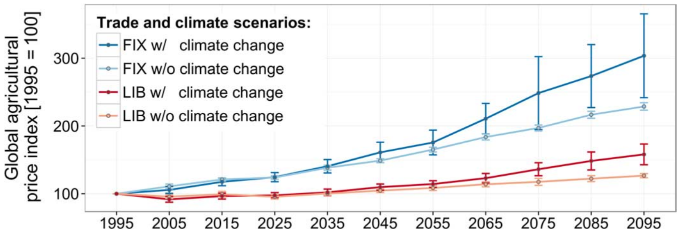

Fig. 3. Global agricultural price index (for all commodities; SRES A2 scenario; without CO_2 fertilization effect). Mean value across GCM scenarios with the 1 SD bars for LIB and FIX trade scenarios, with and without climate change effect.

Trade liberalization is also a suitable measure to prepare for the uncertainty in climate change, especially with respect to the uncertainty in spatial patterns of climate change impacts. Uncertainty in the LIB trade scenario is considerably reduced because of the adaptive potential of trade. In a world with liberalized trade, it is easier to respond to climate change impacts, and especially to impacts from extreme weather events and subsequent fluctuations in agricultural production, by spatially reallocating agricultural production. Moreover, all climate scenarios in the LIB scenario are almost certain in the sign of the impact (after 2065) measured by all indicators, that is, producer surplus is always positive, whereas consumer surplus and overall agricultural welfare are always negative (red shaded area in Fig. 2). On the other hand, the uncertainty in the FIX scenario is much larger because spatial differences in GCM climate projections contribute to the substantial uncertainty in the magnitude of impacts if regional production patterns are inflexible to respond.

Regional climate change impacts

Climate change increases the prices for consumers independently of a trade regime in international agricultural commerce (Fig. 3), affecting almost all regions with negative change in consumer surplus. Distinctively for liberalized markets (LIB), a large part of the agricultural production is shifted to the northern temperate zones under climate change, mainly because of improving environmental conditions for agriculture (fig. S1) and increased comparative advantage (export is more than doubled in high-latitude regions NAM, EUR, and FSU compared to the scenario without climate change, reaching ~160% larger aggregate export volume in 2095; fig. S3), implying that producers in these regions can thus benefit more strongly, entirely compensating the loss in consumer surplus. For example, in EUR and FSU (see caption of Fig. 4 and the Supplementary Materials for the regional acronyms), the created added value for the agricultural sector in 2095 accounts for approximately 0.5 and 1.3% of projected regional GDP, respectively (US$100 billion each), and around 0.5% of projected regional GDP in NAM (US$60 billion) (Fig. 4 and table S3). Regions at lower latitudes lose in agricultural welfare, where total damage in terms of loss of projected GDP ranges from −1.5% in SAS to −0.5% in PAS (Fig. 4 and table S3). These losses are driven by the opposite dynamics, reduced market shares, and thus lower production and producer surplus, but similar reductions in consumer surplus as in the high-latitude regions, because domestic prices are dominated by the world market price under LIB trade scenarios.

On the other hand, if the regional relative agricultural import and export shares are kept constant to historic shares (FIX), impacts of climate change become more accentuated between the individual regions. For the regions in higher latitudes, climatic change does not pose a serious long-term risk to agricultural welfare. Most of these are exporting regions by historical trade patterns, most dominantly NAM, followed by EUR, and, after the mid-century, by PAO. In exporting regions, potential positive impacts on welfare are typically distributed to producers who profit from increased demand driven by global population change and from rising agricultural prices. This, in turn, has an adverse effect on domestic prices because domestic marginal cost of production rises with augmented domestic production for exports. The magnitude of loss in consumer surplus in the exporting regions is almost equivalent to the gain in producer surplus, resulting in a negligible impact on total agricultural welfare in these regions. Consumers benefit only if a region is not a net exporter, and climate change positively influences domestic production (for example, FSU).

Unlike higher-latitude regions, the exporting regions in lower latitudes in the FIX scenario, such as LAM, experience more severe climate change impacts on crop yields, and as a consequence, the magnitude of loss in consumer surplus outweighs potential benefits on the producers' side, reflecting increasing domestic prices. The same dynamics are observed for other tropical and subtropical regions that are more import-oriented. The most dominant negative impacts on agricultural welfare occur in MEA and SAS (Fig. 4, figs. S4 and S5, and tables S3 to S5). Both regions are characterized by significant biophysical limitations for agricultural production (land and water), and if trade barriers are high, increasing agricultural demand will put further pressure on the supply side. Already in 2045, the climate change damage in these regions will account for 1.2 and 1.4% of their assumed GDP and, by the end of the century, will reach 4.6 and 3.1%, respectively. Other importing regions in the FIX scenario follow with negative climate change impacts but to a lesser extent, with the loss in agricultural welfare attributed to climate change ranging from 0.6% of regional GDP in CPA to 1.3% of that in AFR.

Also at the regional level, liberalization of trade appears to represent a good adaptation option to climate change in agriculture. Compared to the welfare losses in the FIX trade scenario, economic climate change impacts can be abated by liberalized trade for almost all regions throughout the entire century. Regions in the northern hemisphere, where agricultural production is often constrained by cold

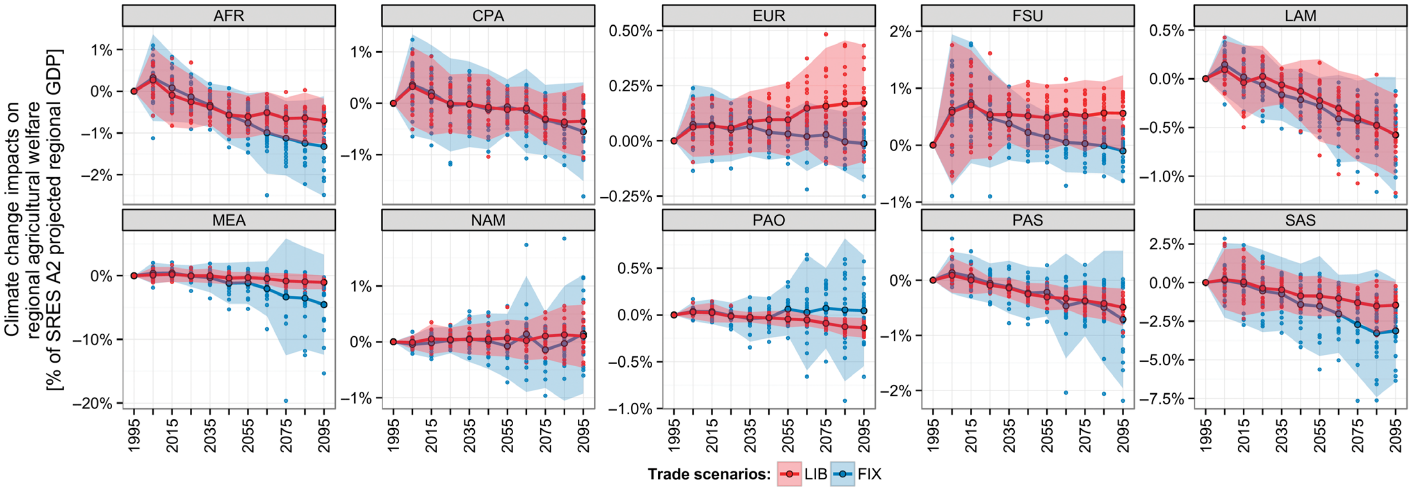

Fig. 4. Climate change impacts on regional agricultural welfare (% of projected regional GDP in the SRES A2 scenario; without CO_2 fertilization effect). Average values (lines) and uncertainty (double SD from the mean; shaded area) across different climate model projections (see Fig. 2). The figure shows outcomes for the 10 socioeconomic MAgPIE regions: AFR (Sub-Saharan Africa), CPA (Centrally Planned Asia), FSU (Former Soviet Union), EUR (Europe, including Turkey), LAM (Latin America), MEA (Middle East–North Africa), NAM (North America), PAO (Pacific OECD), PAS (Pacific Asia), and SAS (South Asia).

temperatures, profit from climate change and liberalized trade because their export increases faster than that in the FIX trade scenario. Consumers in tropical and subtropical regions benefit the most in the LIB scenario. Although the level of consumer surplus will still decrease with intensifying climate change, the loss is considerably reduced in contrast to that in the FIX scenario. Furthermore, big importing regions, such as MEA and SAS, substantially abate climatic impacts on agricultural welfare by taking advantage of lower global agricultural prices compared to the prices under the FIX scenario. They lose 1.1 and 1.5% of their projected GDP in 2095, respectively. Opening up to the world market dampens domestic prices through increased regional import for some goods, which then reduces the amount of the same goods produced locally and cuts producer surplus. Historically exporting regions in the low latitudes, such as LAM and PAO (fig. S3), see stronger climate change impact on agricultural activities and gradually lose their share in the global market in the LIB scenario because excess agricultural production is displaced to more favorable regions.

Uncertainties in the results

Despite the existing uncertainties from climate model projections (GCMs), our results show clear negative climate change impacts on global agricultural welfare toward the end of the 21st century in the socioeconomic scenario of SRES A2 (Fig. 2 and table S1). Notably, the magnitude of the impacts significantly depends on the degree of international trade liberalization. We focus our analysis on the SRES A2 scenario here because patterns are easier to identify under strong changes in population, emitted GHG, and climate as represented by the SRES A2 scenario. However, our general findings are robust against the choice of the socioeconomic scenario (see the analysis of SRES B1 and A1B in addition to A2 scenario in the Supplementary Materials, fig. S6, and table S6). Results show that the patterns of impacts are preserved; that is, although producers will benefit from climate change at the global level, consumers will suffer, and the total impact on agricultural welfare will be negative. In addition, trade proves to have an even greater potential to buffer the damage. However, the overall level of damages decreases with lower population growth rates and lower emissions of GHG, and thus, limited climate change.

The assumption of inelastic demand in MAgPIE could be partly responsible for the high price response under a climate shock and for the related potential upward bias in the estimated monetary impacts. We test for the sensitivity of price indices if consumers would ex post reduce their demand according to the anticipated rise in prices in our standard LIB scenario with climate change effect (Fig. 5 and table S7). The results indicate that this reduction in demand would only slightly offset the global price shock from climate change. The highest demand reduction and consequent decline in agricultural prices are observed in the tropical regions that are affected more strongly by climate change (Fig. 5 and table S7). In addition, the low price elasticity of food as a necessity good further decreases with development because the share of the value added from primary products declines relative to other factors in agricultural value chain (*33*). Because stronger climate impacts are projected to occur mostly in the second half of the century, many of the current low-income countries will be more developed and have less elastic demand responsiveness to prices in the future (fig. S7). As indicated by many other agro-economic models, the response of demand to increasing food prices is relatively small (*33*, *34*); thus, the bias from inelastic demand in MAgPIE should not be a key determinant in the projected impacts.

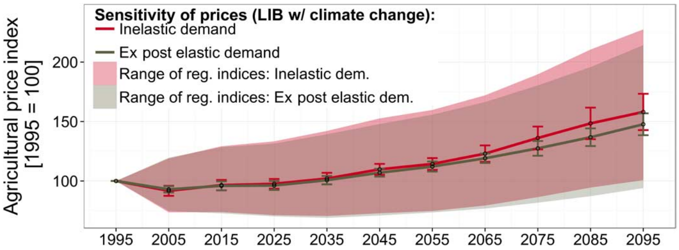

Fig. 5. Sensitivity of prices. Analysis of an ex post demand reduction effect on agricultural price index for the LIB scenario with climate change. Lines connect global index mean values across all GCMs. Bars display 1 SD from the mean. Shades show the range of regional price indices.

The potential overestimation in producer surplus could also stem from the assumption that demanded quantities are not affected by price change, although regional supply could still be altered through international trade channels. Because there is no deadweight loss in welfare since the demand is inelastic, any further input of marginal land with lower yields would raise the price and increase the profit gained on more fertile areas. However, inferring from the uncertainty test for the demand curve, the overstatement of producer gains also could not be large enough to influence the derived conclusions.

Another aspect of uncertainty in the results is the simulated crop productivity under changing climate conditions (*5*, *28*, *35*). Variations in yield projections among global gridded crop models (GGCMs), such as LPJmL, which is used in this analysis, stem not only from different modeling approaches but also from a choice of representing important biochemical processes and parameterizations that are crucial for plant growth (*5*). We compare the results from the LPJmL-MAgPIE modeling suite by deriving MAgPIE simulations with biophysical climate change impact projections on crop yields from four other GGCMs for the SRES A2 socioeconomic scenario but with only one climate scenario (GCM) (Fig. 6 and table S8). The uncertainty in magnitude of impacts across different GGCMs is considerable (0.1 to 1.7% loss of projected global GDP in 2085 in the LIB scenario); however, the general patterns are robust against the choice of GGCM. The magnitude of impacts strongly depends on the choice of GGCM and, most prominently, on the assumption of the effectiveness of CO_2 fertilization (Fig. 6). Here, we contrast results from two crop models that account for the CO_2 fertilization effect: LPJmL and pDSSAT (parallel Decision Support System for Agrotechnology Transfer) (*36*). Both crop models indicate that CO_2 fertilization effects could more than counterbalance the welfare losses compared to cases when CO_2 effect is not considered. The maximal compensation of losses happens around mid-century (144 and 124% offset in 2045 for LPJmL and pDSSAT, respectively) when CO_2 fertilization contributes to overall positive impact on global agricultural welfare (an increase of 0.1% of global projected GDP). However, our sensitivity analysis shows that for both scenarios that assume full effectiveness of CO_2 fertilization, the beneficial influence on agricultural markets cannot compensate for climate-driven damages toward the end of the 21st century. The effectiveness of CO_2 fertilization to translate into higher agricultural productivity at field scale is highly debated and can also reduce the nutritional value of crops (*3*, *25*, *26*, *37*, *38*). More research not only on the biophysical effects but also on implications for agricultural market response is needed in this respect.

DISCUSSION

We find that high-end climate change impacts on crop yields lead to increasingly negative impacts on global agricultural welfare toward the end of the 21st century because consumer losses outweigh producer benefits. However, those impacts could decrease in magnitude with slower future demographic development, reduced climate change impacts, or reduction in demand in agricultural markets, or they could even be offset if positive atmospheric CO_2 fertilization effects on crop yields can be realized at large scales. Global warming and free trade favor agricultural production at higher latitudes and benefit agricultural welfare there despite increasing domestic prices and losses in consumer surplus. Still, positive impacts on total agricultural welfare in EUR and FSU are subject to large uncertainties from climate change projections (GCMs).

Global economic damage, measured as agricultural welfare loss, can reach the annual amount of roughly 0.8% of projected GDP at the end of the century if the international trade is inelastic at 1995 patterns over the simulation period (1995–2095). This estimate can be seen as the high-end value of agro-economic damage, in a scenario with strong climate change without CO_2 fertilization effect on crop yield, under the assumption of inelastic demand and without further elimination of world trade distortions. However, extreme weather events that are likely to increase in frequency and strength with climate change (*39*) are not captured by our model; neither does it capture soil degradation or eventual pests and diseases (*40*) nor effects of climate change on other economic factors, such as labor productivity (*32*). Similarly, trade liberalization could not only stall but also deteriorate to an even more restrictive regime than that of 1995. By gradually liberalizing trade, this damage can be reduced by approximately 65% (that is, to 0.3% of GDP or a loss equal to 6.8% of agricultural GDP on the basis of the estimated 4.2% share of agricultural GDP in total GDP at the end of the century; table S9). The importance of trade in determining impacts on prices, and consequently on welfare, is clearly demonstrated in our analysis (Fig. 3). However, given the difficulties in defining a metric that works for both drivers, it is hard to conclude if trade regimes are more important than climate change or vice versa, or if the relative importance of trade and climate change simply reflects how different the scenarios for each driver are. To contrast the importance of trade impacts against the importance of climate impacts, one would need to use a wider range of trade scenarios and corresponding climate change projections to obtain a robust insight on relevance rank of both drivers.

Although an open trade policy that allows for increasing flows in agricultural commodities is a good way to adapt to future climate impacts, certain caveats apply. Trade liberalization could have major consequences on the environment because increasing agricultural production in favorable locations could lead to additional GHG emissions, for example through deforestation, increased use of fertilizers, or intensified livestock production (*13*). The link between trade liberalization and potential environmental impacts calls for a closer integration of trade and environmental policies in international negotiations (*41*).

Free trade cannot entirely compensate monetary losses in agriculture caused by climate change. Moreover, this damage is unequally distributed between consumers and producers and among different sociogeographic regions. Even in the case of liberal trade, certain consumers and producers will be worse off. There is a clear tendency that consumers in all regions will end up paying more for agricultural products. On the other hand, given that many subsistence and smallholder farmers live in developing regions, policies will have to be advanced to help them to adapt their production under changing market conditions (*42*). In light of the recent Bali Package trade agreement (*43*), which was part of the Doha Development Round trade negotiations within the World Trade Organization (*44*), appropriate policy reforms can be justified based on this study because trade liberalization is beneficial for abating climate change impacts on agricultural welfare. However, regions that are bound to see decreases in export shares as a consequence of climate change (for example, LAM in our analysis) have an incentive to implement policies to support domestic production, for example trade barriers or export subsidies to domestic producers, which could

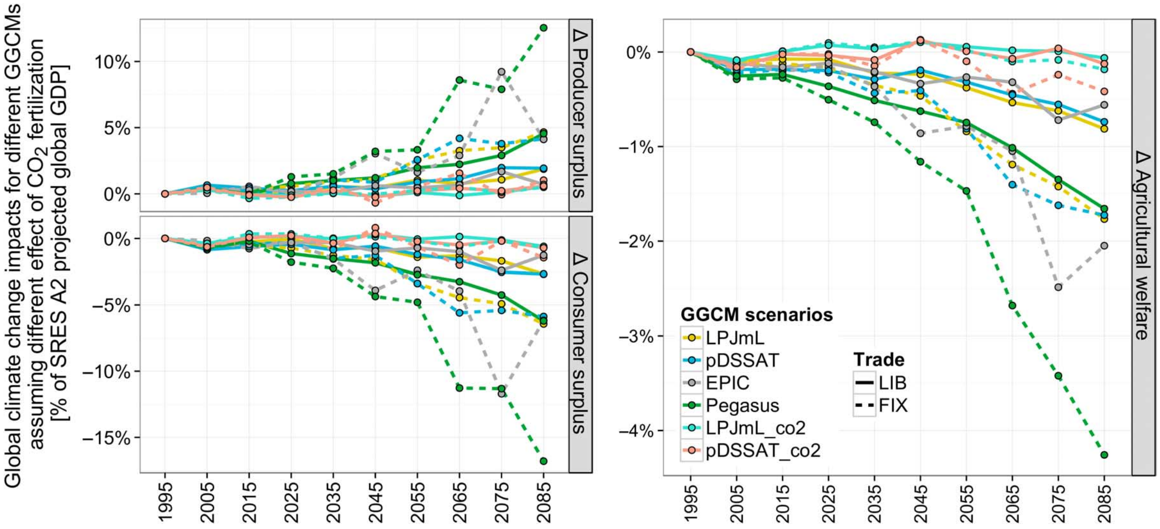

Fig. 6. Global climate change impacts on agricultural welfare indicators for different global gridded crop models. LPJmL (*27*, *28*), pDSSAT (*36*), EPIC (Environmental Policy Integrated Climate) (*49*), and Pegasus (*50*) without CO_2 fertilization effect and LPJmL and pDSSAT with CO_2 fertilization effect. Estimated impacts are simulated under HadGEM2-ES RCP8.5 climate projection and SRES A2 socioeconomic scenario. The GGCM data are obtained from Rosenzweig *et al.* (*5*) as used in the study of Nelson *et al.* (*29*), with projections running until 2085.

diminish economic gains in higher-latitude regions. Given the amplifying effect of climate change on the gradient between developed and developing countries, trade policies will also have to be accompanied by measures for poverty reduction in developing countries. Food security measures have to be actively supported, and the agents' adaptive capacity to the dynamics of liberalization has to be taken into account.

MATERIALS AND METHODS

The main tool in this analysis is the MAgPIE partial equilibrium model (see the Supplementary Materials; fig. S2) (*13*, *16*, *17*, *23*). On the basis of a regional demand for agricultural products and biophysical endowments on a regular geographic 0.5° × 0.5° grid resolution, the model generates optimal land use patterns by minimizing global production costs. The recursive dynamic nature of the model is reflected in a 10-year time-step optimization from 1995 to 2095 through the linkage between optimal land use patterns from the previous period that are taken as a starting point for the current period. The initial period is calibrated to the arable area reported by the Food and Agriculture Organization (FAO). At the top level, MAgPIE operates on 10 socioeconomic regions. The demand for food is regionally defined and given as an exogenous trend to the model, encompassing 16 crop and 5 livestock types. The estimates for calorie intake for each region are obtained from a country cross-sectional regression analysis on population and GDP (*23*). The future demand projections are based on the SRES scenario storylines. In addition to food, the agricultural demand consists also of feed, material, and bioenergy demand. Feed demand is based on feed baskets defined for each livestock production activity and depends on regional efficiencies, whereas the material demand is implemented in proportion with food demand. In this model setting, we account for first-generation bioenergy demand, which is established on current land-based fuel production policy targets (second-generation bioenergy demand is omitted in this analysis).

The supply side in MAgPIE is determined by different production costs, biophysical crop yields, and availability of water. The information on rainfed and irrigated crop yields, water availability, and water requirements for every grid cell are provided by the LPJmL model (*27*, *28*). LPJmL is a dynamic global vegetation, hydrology, and crop growth model that simulates biophysical and biogeochemical processes in plant growth, taking into account all relevant climate factors (temperature, precipitation, radiation, and CO_2) and soil and land use types. Climate projections of 19 GCMs from the CMIP3 (Coupled Model Intercomparison Project phase 3) project (*45*) were bias-corrected and supplied to LPJmL as monthly data fields of mean temperature, precipitation, cloudiness, and number of wet days.

The objective function of the optimization process is to minimize global agricultural production costs. Because the demand is inelastic, the main decision on how to allocate land for cropping activities is based on production costs and interregional restrictions on trade. In the MAgPIE model, four different types of costs are defined: factor requirements, technological change, land conversion, and transport costs. Factor requirements costs are defined per ton of produced crop type and differentiated between rainfed and irrigated production systems. They represent costs of capital, labor, and intermediate inputs (such as fertilizers and other chemicals) and are implemented on the regional scale using the cost-of-firm Global Trade Analysis Project (GTAP) data (*46*). Crop production can be increased in a region by investing in yield-increasing technological change (*47*) or by extension of agricultural production into other nonagricultural areas suitable for plant cultivation (figs. S8 and S9). Land conversion from forest and natural vegetation into arable land comes at region-specific costs. Transport costs are calculated from the GTAP database and assure paying for a quantity of goods transported to the market in a unit of time needed to cover the distance. All MAgPIE regions fulfill part of their demand by domestic production, which is founded on regional self-sufficiency ratios. If domestic production does not cover regional demand, goods are imported from regions with excess production. Export shares and self-sufficiency ratios are calculated from the FAOSTAT database (*48*) for the initial year (1995). Trade between regions can be liberalized in future time periods by relaxing the trade barrier, and thus allowing for a certain share of goods freely traded, on the basis of regional comparative advantage. In every time step, trade is balanced at the global level (*13*).

SUPPLEMENTARY MATERIALS

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/2/8/e1501452/DC1

Supplementary Materials and Methods

fig. S1. Summary of the climate change effect on maize rainfed yield.

fig. S2. Schematic methodological description.

fig. S3. Regional net trade.

fig. S4. Climate change impacts on regional agricultural consumer surplus.

fig. S5. Climate change impacts on regional agricultural producer surplus.

fig. S6. Global climate change impacts on agricultural welfare indicators for SRES A2, B1, and A1B scenarios.

fig. S7. Regional agricultural price index and regional GDP per capita.

fig. S8. Land use intensity index validation.

fig. S9. Cropland validation.

table S1. Climate change impacts on global agricultural welfare indicators.

table S2. Maize consumer price.

table S3. Climate change impacts on regional agricultural welfare.

table S4. Climate change impacts on regional producer surplus.

table S5. Climate change impacts on regional consumer surplus.

table S6. Global climate change impacts on agricultural welfare indicators for SRES A2, B1, and A1B scenarios.

table S7. Sensitivity of prices to an ex post change in demand.

table S8. Global climate change impacts on agricultural welfare indicators for different global gridded crop models.

table S9. Summary of climate change welfare effects as changes in total and agricultural GDP.

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