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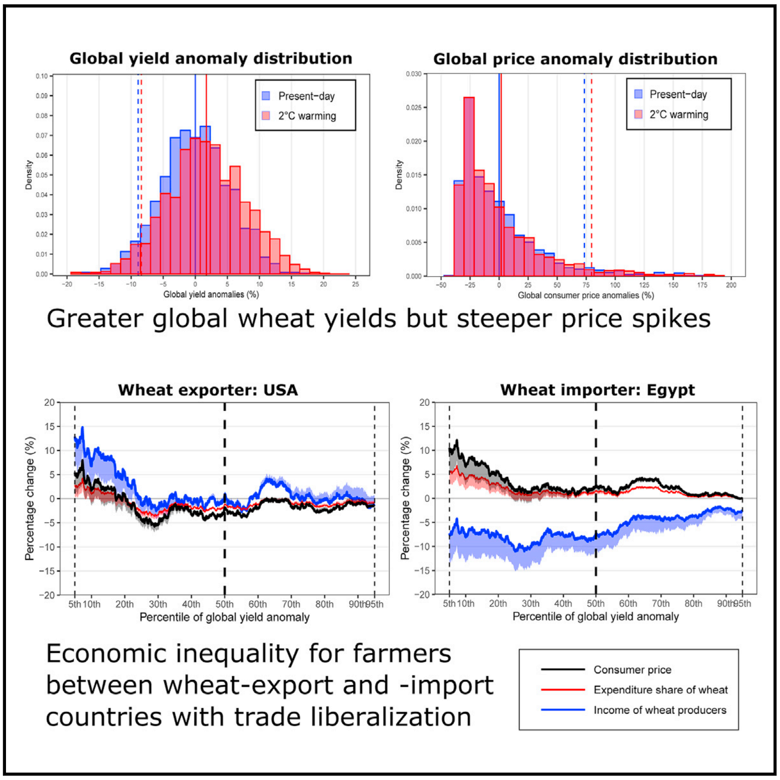
Increased wheat price spikes and larger economic inequality with 2°C global warming

Graphical abstract



Highlights

- Greater global wheat yields but steeper price spikes under 2°C warming
- 2°C warming deepens traditional global wheat trade spatial pattern
- Trade liberalization could expand economic inequality for wheat farmers
- Trade liberalization accompanied by protection policies is needed

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In brief

Zhang et al. assess the impact of 2°C warming on the global wheat supply and demand chain by using a large-ensemble integrated modeling approach. They anticipate that climate change will cause greater wheat yields but also steeper price spikes at a global scale, reconstructing the wheat supply and demand chain. Rather than mitigating it, a trade liberalization policy could further expand economic inequality for farmers in wheat-exporting and -importing countries under a future 2°C-warming scenario.

Zhang et al., 2022, One Earth *5*, 907–916
August 19, 2022 © 2022 Elsevier Inc.
https://doi.org/10.1016/j.oneear.2022.07.004

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Increased wheat price spikes and larger economic inequality with 2°C global warming

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https://doi.org/10.1016/j.oneear.2022.07.004

SCIENCE FOR SOCIETY The latest research shows that warming can be kept just below 2°C if all Paris Agreement pledges are fulfilled. Such a warming will result in changes in the climate and its variability, which could potentially affect the production and supply demand of key food commodities, such as wheat. Most studies have investigated climate impacts on wheat yield, but what 2°C warming will bring to global wheat consumers and farmers is still unknown. We anticipate that global wheat price spikes will become more frequent despite an increase in wheat yield given that CO_2 fertilization compensates for warming stress. This will pose more economic stresses on wheat-product consumers. On the supply side, the income gap between farmers in wheat-exporting and -importing countries will be further expanded with trade liberalization under a 2°C-warming climate scenario. We believe that climate change impacts on the global wheat supply and demand chain cannot be ignored even though CO_2 fertilization could largely benefit wheat yields.

SUMMARY

Climate change poses complex impacts on the global wheat supply and demand chain. The impacts of climate change on average wheat yields are reasonably well studied, but its effects on yield variability and the associated economic consequences are poorly understood. Here, we show that future global wheat prices will exhibit steeper spikes at 2°C global warming (6.2% increase in the 95th percentile of global consumer price anomalies) despite a 1.7% increase in production given that CO_2 fertilization benefits crops. Such economic stresses could be abated by trade liberalization with lower prices. However, on the supply side, trade liberalization has contrasting effects: the profitability of farmers in advanced economies can be maintained or even raised, but this will inevitably cause economic losses and inequalities for farmers in less-developed, wheat-importing countries. Agricultural trade liberalization accompanied by protection policies in developing countries would be beneficial for global food security in the threat of climate change.

INTRODUCTION

Wheat is the world's major grain crop in that it provides 20% of the protein and calories for more than 3.5 billion people in 94 countries.[1] Its production, availability, and accessibility are therefore vital for global food security. Unfortunately, climate change puts substantial stresses on wheat production in many important production regions.[2–5] Globally, an average yield loss of 4%–5% per degree warming is anticipated,[5,6] without considering CO_2 fertilization effects. Besides long-term mean climate stress, yields also become more volatile due to the increasing frequency and severity of extreme weather events.[7] Increased yield variability often leads to rapid food price inflation, disseminating significant economic signals on the global agricultural supply and demand chain. Short-term price volatility due to long-term climate change poses substantial stresses on future global food security and will put society's poor at greater risk.

To achieve the long-term target of the Paris Agreement,[8] countries need to purse efforts to limit the temperature increase to 1.5°C and keep warming to well below 2°C relative to the pre-industrial period. This requires countries to update and progress their 2030 mitigation goals in their nationally determined contributions (NDCs) and long-term low-emission development strategies (LT-LEDS). A recent analysis[9] considered updated NDCs and LT-LEDS by mid-November 2021 and indicated that warming can be kept just below 2°C (1.9°C–2.0°C) if all conditional and unconditional pledges are implemented in full and on time. Therefore, although not ideal, a 2°C warming is a more realistic scenario to analyze potential impacts on global food supply. Given the importance of wheat to feed the global population, investigating the potential impact of climate change and variability on the supply and demand chain of global wheat in a 2°C-warmer world is essential to anticipate the future magnitude of food-security challenges.

Existing modeling studies evaluate yield[2–5] and economic[10] responses to mean climate change based on a multi-model ensemble,[2–5] but such a modeling approach often does not fully capture the future impacts of changing climate variability and extremes, particularly at the regional scale, because most models have only a limited number of realizations.[11] Therefore, a comprehensive understanding of the impacts of changing climate variability and extremes is still lacking. By contrast, large initial-condition ensembles, whereby a single climate model is re-run multiple times and initiated with slightly different initial conditions each time, could better capture the range of future regional climate variability possible due to climate change in the presence of internal climate variability.[11–13]

In this study, we used an integrated climate-impact large-ensemble modeling approach by combining a global climate model (EC-Earth[14] v2.3), a wheat growth model (APSIM-Wheat[15] v7.10), and a general equilibrium economic model (GRACE[16]) to address three main questions: (1) how the climate affects wheat yields and prices in both average and variability with 2°C global warming, (2) how this reconstructs the supply and demand chain of global wheat, and (3) whether trade liberalization is helpful to mitigate impacts of climate change and variability. Analyses employing the integrated modeling approach anticipate that the combined effect of future 2°C warming and CO_2 fertilization will result in a greater global wheat yield but steeper price spikes. Trade liberalization under the future climate will expand the income gap between the farmers in wheat-exporting and -importing countries, which deteriorates grain self-sufficiency of the wheat-importing countries. Our study provides a reminder that climate change and variability impacts on the global wheat supply and demand chain cannot be underestimated, even though CO_2 fertilization could largely compensate for warming stress on wheat yield.

RESULTS

Greater global wheat yields but steeper price spikes

We divided the world into 51 socioeconomic regions, including not only the global major wheat-producing countries but also the important exporting and importing countries in each continent (Figure S1). An extensive model validation was conducted (experimental procedures); the three models were compared with historical climate, yield, and price observations (Figure S2) and with previous multiple-model projects[2] (Figure S3). These results suggest that our model approach not only reproduces the realistic climate variability, yield, and price dynamics but also is comparable with results from other models, which together provide adequate confidence in the model chain and the realism of the experimental outputs.

Using this modeling framework, two large ensembles of climate simulations were generated to represent the climatology in a "present-day" (2011–2015) scenario and a "2°C-global-warming" scenario. For each scenario, we simulated 1,600 seasons of wheat yields with both climate change and CO_2 fertilization effects, which in turn were aggregated from grid points to the country level and fed into the economic model to examine how changes in both mean yield and yield variability affect wheat prices. We calculated yield anomalies, which were defined by percentage yield deviation in each growing season relative to the average value of yield in the present-day scenario. The 5th and 95th percentiles of anomalies were studied to present changes in extremes (experimental procedures).

On the basis of the simulation, we anticipate a 1.7% increase in global mean yield under 2°C warming relative to the present-day climate and widened yield variability (increase from 17.8% to 20.3% in the 5th–95th percentile range), where the 5th percentile of global yield anomaly (i.e., 1-in-20-year global low-yield extreme) is higher by 0.5% (Figure 1A). The primary reason for these yield increases is the CO_2 fertilization effect, which compensates for the negative impact of warming. In our simulations without CO_2 fertilization, there is a global decrease in mean yield of 6.6% (Figure S4). At the regional scale, lower-latitude regions show a remarkable yield decline (e.g., Africa and South Asia), whereas some higher-latitude areas (e.g., the US, China, Europe, Oceania) can expect a yield increase (Figures 1C and 1E).

Perhaps counterintuitively, the global yield increase does not result in a lower consumer price. Instead, the average global wheat price for consumers (weighted by the export shares) increases by 1.8%, and the 95th percentile rises by 6.2% (Figure 1B). The greater magnitude of price for the 95th percentile suggests an additional increase for a high-price extreme event relative to the global mean price. Global consumer price spikes become more frequent in the future 2°C-warming scenario; a price-spike event that would have occurred once every 20 years

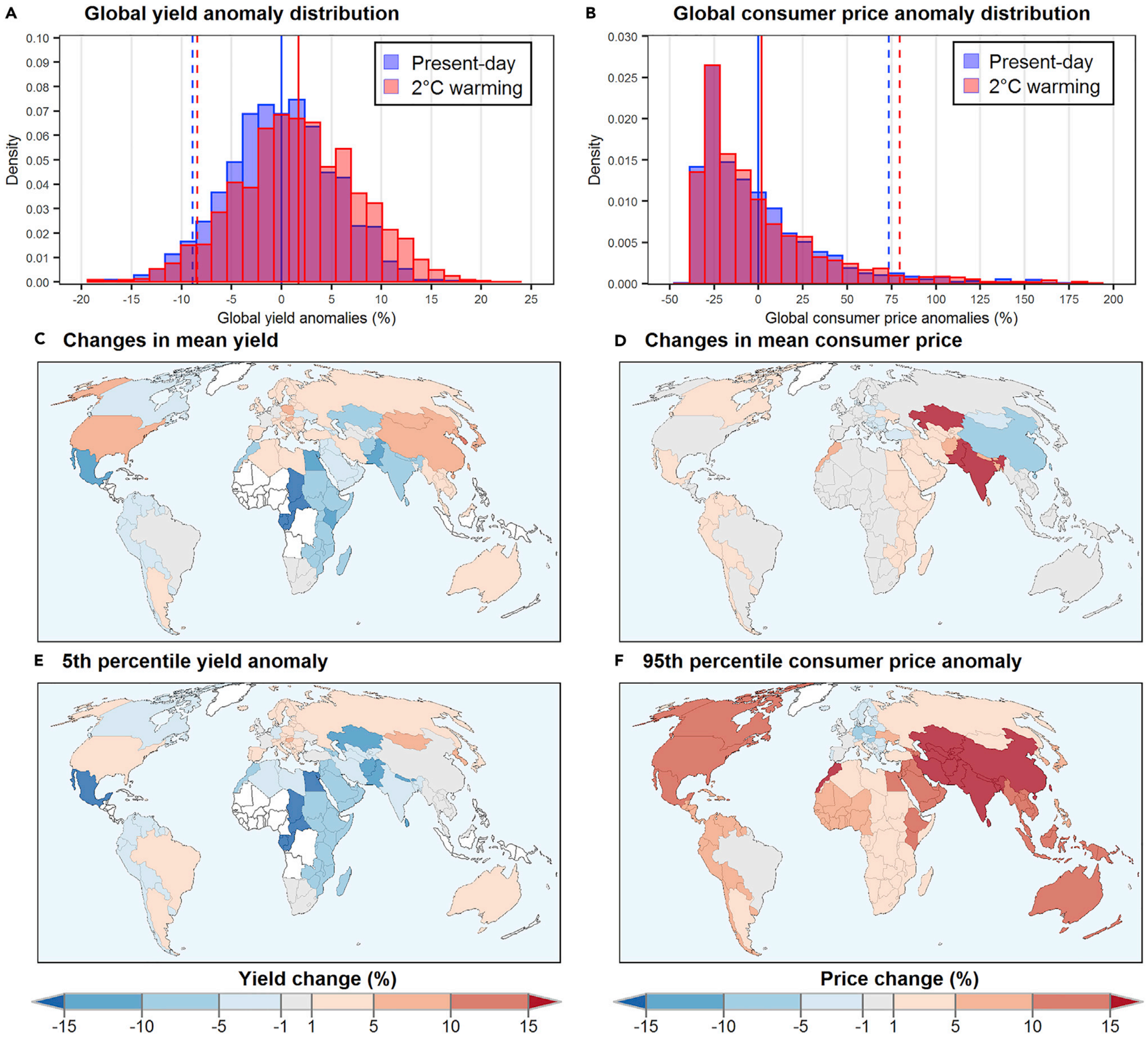

Figure 1. Impact of 2°C warming on global and regional wheat yield and consumer price with CO_2 fertilization effects

(A and B) The impact on the distribution of global wheat-yield and consumer-price anomalies (relative to the mean in the present-day scenario); solid lines denote the mean yield change (A) and mean price change (B), and dashed lines denote the 5th percentile of global yield anomaly (A) and 95th percentile of global consumer price anomaly (B).

(C and D) Percentage changes in mean yield and price within each socioeconomic region.

(E and F) The change in 5th percentile of yield anomaly (E) and 95th percentile of price anomaly (F) by socioeconomic region.

in the present-day climate might become as frequent as once every 17 years with 2°C warming. Only results for the export-weighted global consumer price anomaly are reported in the main text for consistency with the FAO price index.[17] However, projected price-spike increases are even steeper when wheat production or population shares in each socioeconomic region are used for calculating weighted-average values (Figure S5), which show 17.3% and 21.4% increases in the 95th percentile of global consumer price anomaly, respectively. For each socioeconomic region, we find an increase in mean prices at 2°C warming, where the largest increases are in India and Central Asian countries (Figure 1D). However, some countries experience a decrease in mean prices, most notably China but also some European countries given that local yields are increased and the price of domestic produce is reduced (Figure 1D). Results for the 95th percentile of global price anomaly are more spatially consistent (Figure 1F), with most countries demonstrating steeper price spikes, except for a few European countries.

To illustrate the reason for the simultaneous increase in both global yield and price, we show the simulated global low-yield events (5th percentile of global yield anomaly) in the 2°C-warming and present-day climate scenarios and compare the differences

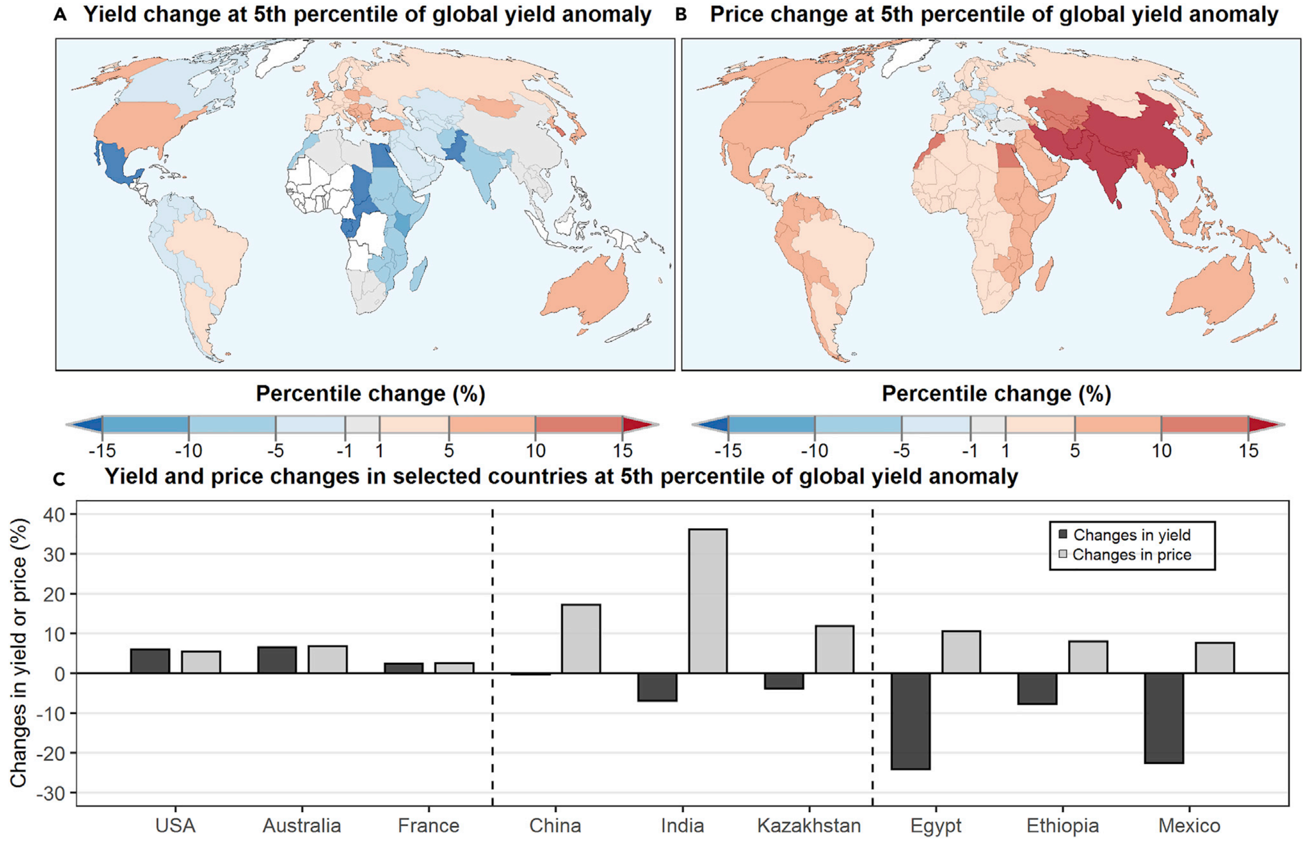

Figure 2. Changes in wheat yield and consumer price at 5th percentile of global yield anomaly
Global description (A and B) and results for several selected countries (C).

of yield and price anomalies in each region (Figure 2). The increase in the 5th percentile of global yield anomaly (Figure 1A) comes from the yield surpluses in the high latitudes (Figure 2A), where many large wheat-exporting countries produce more wheat (e.g., the US, Australia, and France in Figure 2C). Such yield increases compensate for the lousy harvests in low latitudes (Figure 2A); for example, India sees yield reductions of 6.9%, and Egypt loses as much as 24.2% of yields (Figure 2C). The countries with increased yields profit from the higher prices, which are the result of decreased yields in major wheat-importing nations (Figure 2C). This results in a higher global price anomaly in the 2°C warmer climate than the present day when the 5th percentile of global yield anomaly is considered (Figure 2B). High-latitude countries with greater yields are traditionally wheat-exporting countries. With intense global yield demands from the importing countries with lower yields and the resulting higher prices there, this boosts wheat export in traditional wheat-exporting countries (Figure S6). This also stimulates their domestic wheat prices, which together contribute to the steeper price spikes at the global scale (Figure 1B). Finally, the spatial distribution of yield and price extreme is robust given that the results are similar for other percentile yield and price anomalies (Figure S7).

Varying demand and supply profiles with global yields

Next, we investigate wheat demand and supply profiles for various global yield levels. These are shown as percentage changes of the share of wheat consumption in total household expenditures and income from wheat, respectively, and are relative changes in the 2°C-warming scenario compared with the present-day climate at equal percentiles of global yield anomaly (Figure 3). On the demand side, for the wheat-exporting countries (e.g., the US, Australia, and Canada in Figures 3A–3C), there is a marginal difference (± 1%) in the expenditure share of wheat between the 2°C-warming scenario and the present-day climate when global yield is higher than 20th percentile of global yield anomaly. But, when it is lower than the threshold, higher expenditure shares of wheat (no more than 5%) are projected. On the supply side, wheat farmers in the US and Australia are projected to see an increase in income under 2°C warming (Figures 3A and 3B) as a result of greater yields (Figure 1C). This contrasts with Canada, where a lower income is anticipated in most cases as a result of yield reductions (Figures 1C and 3C). However, these countries still benefit economically during global low-yield events when price effects outweigh yield changes. Additionally, we note that despite being an exporting county, India's response during low-yield events differs from that of other regions. India's domestic wheat price is significantly higher in the 2°C-warming scenario than in the present climate. This is beneficial for local wheat farmers but detrimental for consumers in India (Figure 3D).

In contrast, for developing wheat-importing countries (e.g., Egypt and Ethiopia in Figures 3E and 3F), we anticipate a higher expenditure share of wheat and a lower income for wheat

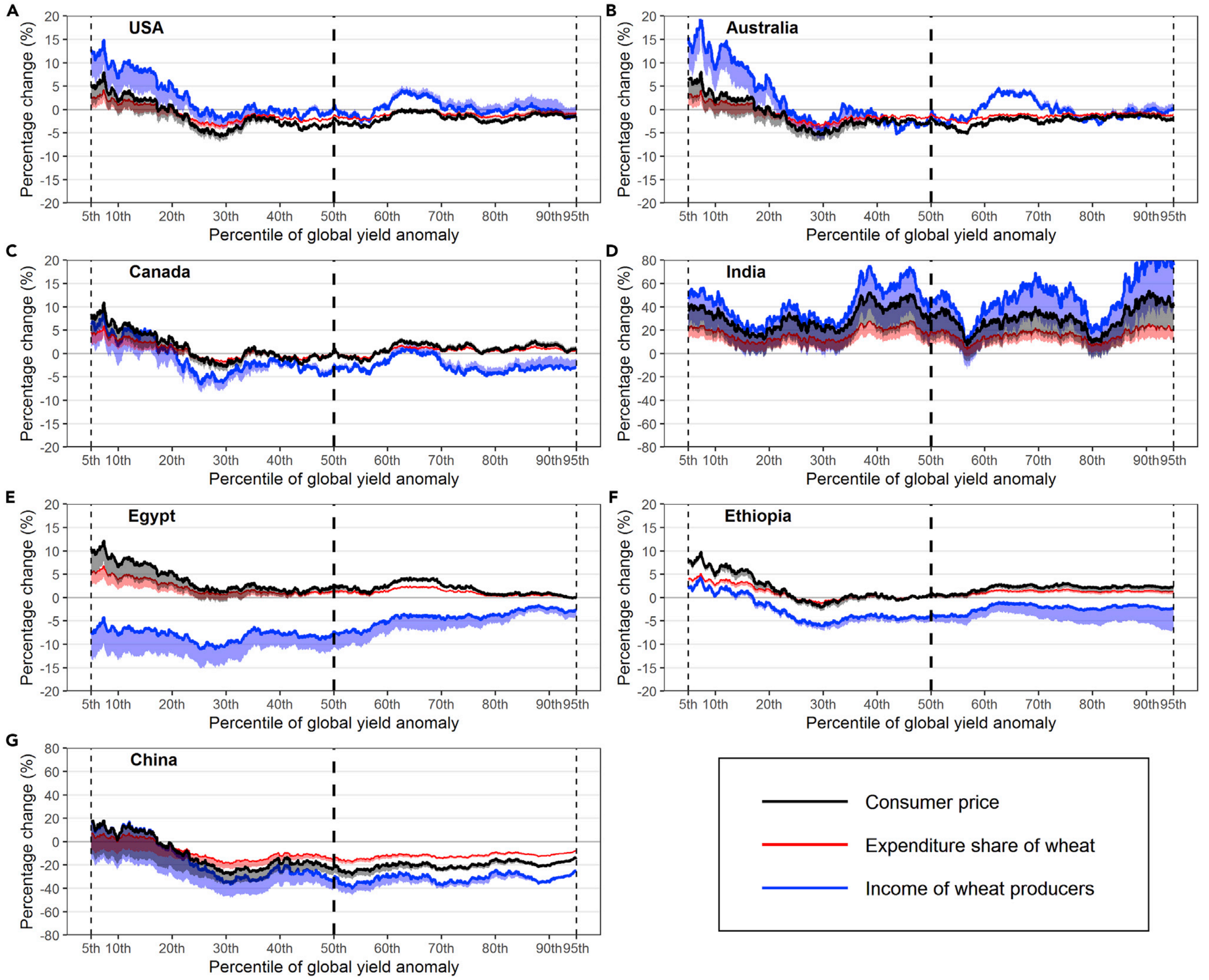

Figure 3. Percentage change in consumer price, expenditure share of wheat, and wheat producers' income in selected countries for different percentiles of global yield anomaly under the 2°C-warming scenario

The shaded areas show the impact of trade liberalization. The selected cases include wheat-exporting regions with increasing yield (A and B), the wheat-exporting regions with decreasing yield (C and D), developing wheat-importing countries (E and F), and China as a large wheat producer (G).

producers, indicating heavier economic burdens for both the demand and supply sides. In China, as a result of higher yields (Figure 2C), China's wheat imports fall, which increases the self-sufficiency ratio and lowers the domestic price to the benefit of the consumers but simultaneously reduces the income for wheat producers (Figure 3G). The income reduction of wheat farmers in China is one of the largest among the socioeconomic regions shown here.

Economic inequality due to trade liberalization

To examine the effect of trade liberalization, we reduce the global trade barriers by 50% relative to the trade regime in 2011 (experimental procedures) and compare the results of the two trade regimes for equal global yield levels. The effect of trade liberalization on the wheat demand side is limited in most regions for the mean projection (Figure 4A) except in Asian countries where lower trade barriers increase demand and imports, thus reducing their expenditure shares of wheat (Figure 4A) and producers' income in South and East Asia (Figure 4B).

At the 5th percentile of global yield anomaly, when supply shortages would normally rise consumer price considerably, trade liberalization can mitigate price increases to some extent and relieve economic stress for consumers (Figure 4C). In contrast, trade-barrier reduction lowers the income from wheat farming in most of the world during the low-yield events given that freer trade reduces the consumer price (Figure 4D). This effect is particularly visible at the 5th percentile of global yield anomaly in our exemplified countries (the shading area in Figure 3), in which we see greater reductions of producers' incomes than increases of consumers' benefits due to price reductions. Note that wheat-exporting regions can still benefit economically during global low-yield events (Figure 3) even though the magnitude of increasing income is reduced under

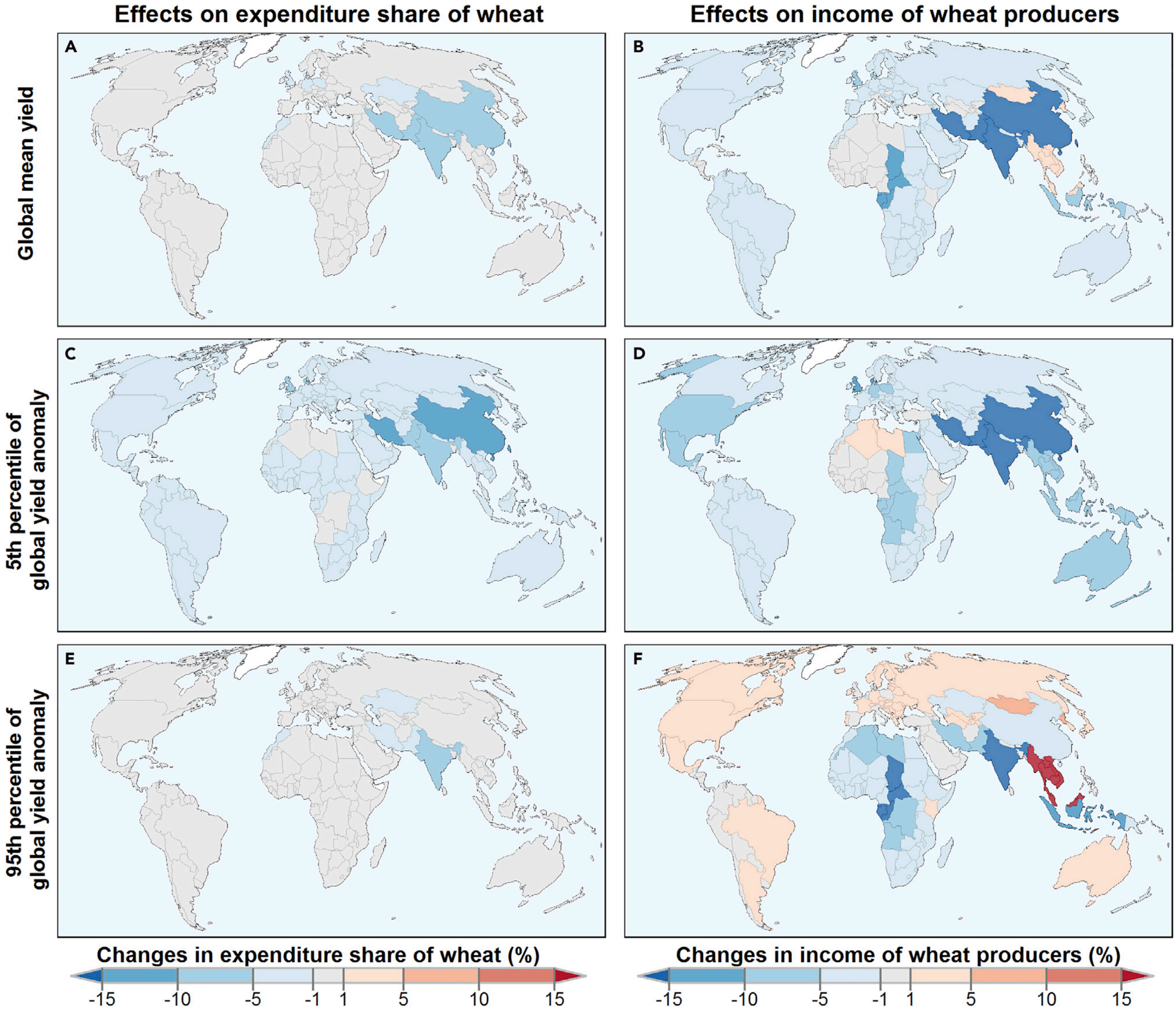

Figure 4. Effects of trade liberalization on expenditure share of wheat and income of wheat producers

The first row shows the mean percentage impact of the 2°C-global-warming scenario (A and B), the second row shows the results at the 5th percentile of global yield anomaly (C and D), and the third row shows the results at the 95th percentile of global yield anomaly (E and F).

a freer trade regime (e.g., the US and Australia in Figures 3A and 3B). In developing wheat-importing regions, where lower wheat yields already reduced incomes, trade liberalization further exacerbates the negative effect on producers' income reduction by lowering the price (e.g., Egypt and Ethiopia in Figures 3E and 3F). At the 95th percentile of global yield anomaly, i.e., global high-yield events, there is no significant difference on the demand side between the trade regimes in most areas (Figure 4E), but the effect of trade liberalization on income differs between wheat-exporting and -importing regions (Figure 4F). There is a growing profitability of producers with freer trade because of stabilized prices and higher yields in these wheat-exporting countries (Figure 4F), but this profitability is at the cost of wheat-importing countries, including many African and Asian countries (Figure 4F), which reduce income despite high wheat harvests globally.

DISCUSSION

Our analysis highlights the net effects of climate change and CO_2 fertilization on global- and regional-specific wheat yields and the associated economic consequences in a 2°C-warming scenario. We find that elevated CO_2 compensates for the increased climatic stresses and results in increased wheat yields globally. Despite this global increase, steeper price spikes are still found. The simultaneous increase in both global yield and price is mainly associated with the imperfect international trade to balance domestic production and consumption in a region. In the future 2°C-warming scenario, the increase in wheat yield happens mostly in net-exporting regions, while the decrease in wheat yield occurs mostly in net-importing regions. Because wheat consumption is largely inelastic to price, the domestic demand in net-importing regions tends to keep constant, although domestic production is reduced, motivating a larger share of imports and pushing up the price in the international market. On the other hand, since the international market is imperfect, the net-exporting regions with increased wheat yield could not supply the necessary additional wheat to the net-importing regions, resulting in two effects: the increased price in the international market, and the decreased domestic price in the net-exporting regions. However, the price in net-exporting regions would decrease at a much lower extent than the price increase in net-importing regions due to the property of inelastic demand for wheat with respect to price. Hence, the global average price weighted by exported wheat tends to increase, although global total wheat production increases. In addition, the consumption in net-importing regions with more population accounts for a larger share of the global consumption, where price increases at a higher extent than the price decreases in net-exporting regions in general, then the global average price weighted by either production or population shares of socioeconomic regions increases at a larger extent.

The yield reduction in wheat-importing regions leads to higher demand and higher price and would deepen the traditional trade patterns between wheat-importing and -exporting countries under 2°C warming. This, of course, has a substantial impact on the global wheat supply and demand chain. In wheat-exporting countries, yield increases not only maintain domestic prices but also raise farmers' income by increased exports and higher prices during global low-yield events. In contrast, wheat-importing countries are driven by opposite dynamics; lower wheat yields and increased imports lead to higher domestic prices in these countries and thus reductions in consumer surplus and farmers' income. The diversity in these responses between net-exporting and -importing countries is consistent with a previous study.[10] Our experiments highlight, however, that such responses greatly vary with global yield levels, which we have been able to capture in our unique large-ensemble experiments. Our results show that the mean impacts do not show the full picture; the impact of the roles of supply-demand chains and associated mechanisms is quite different during global low- or high-yield events and is different from that at the typical yield levels.

In terms of trade liberalization, our results offer important additions and add to existing studies[10,18] that mostly reported that a freer trade regime would result in a lower producer surplus than the normal trade regime as the mean response of climate change at a global scale. Our large-ensemble simulation shows that the effect of a freer trade regime on the producers is also dependent on global yield levels. Trade liberalization has a negative impact on wheat farmers' incomes in developing wheat-importing regions consistently, but trade liberalization stabilizes the income of producers in developed wheat-exporting countries under global yield extreme events, i.e., the income of wheat producers could further increase as a result of more wheat exporting during high global wheat harvest seasons; meanwhile, farmers could still benefit from the higher wheat price in the international market during low global wheat harvest seasons despite the magnitude of the profitability reduced with a freer trade regime. Such an asymmetric outcome for the farmers indicates widening economic inequalities on the supply side between wheat-exporting and -importing countries brought by trade liberalization with 2°C warming. This indicates that farmers in developing wheat-importing regions are vulnerable not only to the negative effects of climate change but also to the potential effects of trade liberalization. Given the fact that wheat is an essential consumption good and shows low demand elasticity in wheat-importing countries, this may aggravate the dependence on import, continuing to reduce income of the less-competitive domestic wheat producers, lowering their wheat self-sufficiency ratio and thus creating a vicious negative cycle.[19] Therefore, international agricultural trade liberalization policies must be accompanied by measures to enhance the ability to produce staple agricultural products in developing countries.

We emphasize that although the food system is complex, our study is focused on the impacts of climate change and trade liberalization only. Our crop model assumed no change in farming practice or agricultural technology (i.e., stress-tolerance breeding,[20] greater irrigation,[21,22] or adjusting sowing windows[23]), nor does our economic model attempt to account for some socioeconomic factors (i.e., global population increase,[24] use of bio-fuels,[25] or changing diet structures[26]). Rather, we interpret our results as the impacts imposed by a change from the present climate to a 2°C-warmer world, including the associated CO_2 fertilization effect, under the existing wheat-producing technologies and socioeconomic-geographic trading patterns in 2011, without considering changes in wheat inventories (e.g., interannual changes in storage, etc.).

To conclude, this assessment, based on an integrated climate-impact large-ensemble modeling approach, suggests that steeper price spikes are anticipated in a warmer climate even if positive atmospheric CO_2 fertilization effects on wheat yields could be realized at large scales and global wheat production was maintained. How to deal with the uneven spatial distribution for yield changes between wheat-exporting and -importing countries with 2°C warming is crucial to maintaining global food security. Trade liberalization is a policy that is often mentioned to mitigate climate extreme shocks by offsetting the impact of localized fluctuations through accessing additional supplies.[27] Under global low-yield extremes, the lower price induced by freer trade is beneficial to the consumers but will expand the economic inequality for the farmers between wheat-exporting and -importing countries. Therefore, large international agricultural negotiations (e.g., G20[28] and Belt and Road Initiative[29]) are instrumental to include effective measures[30,31] to protect wheat industries of importing countries in their trade liberalization policies, to support resilience, and to enhance global food security.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources and reagents should be directed to and will be fulfilled by the lead contact, Tianyi Zhang (zhangty@mail.iap.ac.cn).

Materials availability

This study did not generate new unique materials.

Data and code availability

The data are available in the Zenodo repository at https://doi.org/10.5281/zenodo.6789634. All model codes are available for download: EC-Earth (http://www.ec-earth.org/), APSIM-Wheat (https://www.apsim.info/), and GRACE (https://doi.org/10.17632/xsv6jt53ym.1).

Models

We combine a state-of-the-art global climate model (EC-Earth[14] v2.3), a wheat crop model (APSIM-Wheat[15] v7.10), and a general equilibrium economic model (GRACE[16]) to create the full distribution of climate change impacts on global wheat yields, market prices, and wheat market fundamentals (i.e., demand and supply side). This allows the study the effects of climate change on extreme societal impact events in a robust manner.

Global climate model: EC-Earth

EC-Earth is a coupled global climate model based on the operational seasonal forecast system of the European Centre for Medium-Range Weather Forecasts. Our study used EC-Earth to create two large ensembles of climate data, representing the climatology of the present day and after 2°C global warming. A present-day ensemble consisting of 400 5-year-long realizations were performed for a total of 2,000 years. The simulations were forced with the RCP8.5 emissions scenario for the years 2035–2039. This time period corresponds to when the absolute global mean surface temperature (GMST) from the ensemble mean of the available CMIP5 RCP8.5 simulations matched the observed absolute GMST for the period 2011–2015 from MERRA2 observations,[32] while the 2°C-warming ensemble has a simulated GMST that lies 2°C above observed pre-industrial temperatures.[33] Initial conditions for the 400 realizations were generated by making 25 atmospheric stochastic perturbations branched off from 16 different climate states from the available RCP8.5 simulations. These climate ensemble simulations were previously used for assessing European energy security[34] and changes in global river-discharge extremes.[35]

We note that our climate simulation is based on a single model using a large initial-condition ensembles approach rather than a multi-model approach, which is more traditional in climate and climate-impact science. Although this traditional approach is suitable for projecting changes in mean climate, the limited simulation years per model means that only a small number of wheat growing seasons are available from each model, which leads to substantial uncertainties in the calculation of return intervals of the most extreme events, as pointed out by an earlier study.[11] Therefore, we chose to use the large-ensemble approach here, which provides many simulated seasons for a given climate window and therewith resolves the full distribution of internal climate variability and allows the explicit investigation of extreme events.

Wheat crop model: APSIM-Wheat

The APSIM-Wheat model simulates the wheat growth and development in a daily time step. In this model, wheat crop growth and development respond to climate, soil water and soil nitrogen, and management practices in a range of growing situations. The APSIM-Wheat model can represent the actual CO_2 fertilization effect[36] when the CO_2 concentration was elevated up to 550 ppm in a free-air CO_2 enrichment (FACE) experiment. We ran the model by using daily global climate data generated by the EC-Earth model, producing the wheat yield assessments for the present-day climate and for the 2°C-warming scenarios. As winter wheat's growth spans 2 calendar years, there are 1,600 complete wheat growing seasons (400 groups with 4 years) in each scenario. Following the paradigm of Agriculture Model Inter-comparison and Improvement Project (AgMIP[37]), we simulated both spring and winter wheat growing seasons at the global scale. The sowing data of the two seasons were extracted from Sacks et al.,[38] and grid-based data on irrigated versus rainfed areas are based on Portman et al.[39] For irrigated land, 20 mm irrigation was given when soil water content is less than 80% of the soil water holding capacity. No irrigation was applied for rainfed areas. The average yields were then calculated weighed by the shares of irrigated and rain-fed areas. Nitrogen applications were taken from Muller et al.[31] Soil parameters (including pH, soil total nitrogen, organic carbon content, bulk density, and soil moisture profiles for each of five 20-cm-thick soil layers) were derived from the International Soil Profile Dataset.[40] To specify the cultivar properties, we used the gridded phenological parameters (i.e., thermal time accumulated), which were calculated on the basis of phenology[38] and temperature[32] observations. A CO_2 concentration of 394 ppm was used in the present-day scenario, and 489 ppm was used in the 2°C-warming scenario.

General equilibrium model: GRACE

The GRACE model is a multi-sector, multi-regional, recursively dynamic global computable general equilibrium model. The model describes 14 production activities, of which there are four agricultural sectors, two food sectors, one manufacturing sector, one transport sector, one services sector, and five energy sectors. It simulates the economic responses to the above climate impacts on wheat yields, which is interpreted as climate impacts on wheat production in GRACE in this study rather than changes in productivity of natural resources.[16] This assumption is plausible for this study since wheat producers probably have limited adaptation options to mitigate impacts of the extreme climate events considered in this study. In GRACE, the income of the wheat sector is represented by the valued added of the sector, which is influenced by changes in wheat yields, wheat prices, and quantities and prices of other inputs in the wheat production. The model has been widely employed to investigate the global/regional agricultural economy[41] and climate policy.[42]

We calibrate GRACE by using the Global Trade Analysis Project (GTAP) v9 database[43] with 2011 as the base year, which is consistent with the period of our present-day climate scenario. In GRACE, the world is divided into 51 socioeconomic regions according to the FAO database[44] of wheat production and international trade so that the 51 socioeconomic regions include not only the global major wheat-producing countries and regions but also the important exporting and importing countries and regions in each continent (Figure S1). We assume that the monetary values of wheat production and consumption in the GTAP database are for the physical quantities of wheat production and consumption in the FAO database, respectively. The wheat consumption in each of the socioeconomic regions was firstly satisfied by their domestic production. If the domestic supply cannot meet the domestic demand, wheat could be imported from regions with excess production. The international trade of wheat is balanced at the global level in a given year. Therefore, GRACE can simulate changes in regional supply and demand of agricultural products and describe a variety of economic consequences in the wheat supply chain. Although GRACE has the option to simulate crop production endogenously, in this study we do not invoke the endogenous option and instead assume that the wheat production is exogenously given by the yield simulations from the APSIM-Wheat model, assuming consistency in wheat growing areas across climate scenarios.

In this study, we use the static version of the GRACE model describing the global economy in 2011, where the trade regimes of all products, including wheat, are consistent with the 2011 global economic system. International trade is simulated by the Armington approach,[45] where an elasticity parameter largely determines to what extent a domestic product can be substituted by the same product imported from other regions. To examine the effects of trade liberalization on wheat demand and supply by region, we shift up the values of the elasticity parameters for all products according to the Armington approach by 50% in the 2°C-warming scenario, which implies that the bilateral trade barriers are reduced by approximately 50% globally.[45]

Model validation

The modeling chain starts with the EC-Earth model, from which two large ensembles of climatic data are used. Compared with the MERRA2 reanalysis, the climate model provides realistic simulations of the distribution of daily mean temperature (Figure S2A) and precipitation (Figure S2B) anomalies, especially in major wheat growing areas such as Asia and North America. In the northern part of the South American continent, simulated biases are relatively larger, with a 2°C–3°C underestimation of the standard deviation of daily mean temperature anomalies and 4–6 mm/day overestimation of the standard deviation of daily precipitation anomalies. The model biases for daily minimum and maximum temperature anomalies (Figure S8) are like those for daily mean temperature.

With 2°C global warming, the increase in daily minimum temperature is slightly greater than that in daily maximum temperature, especially in some major wheat growing regions such as northern China, India, and Canada (Figures S9A and S9C). Additionally, compared with those in the present-day climate, the minimum and maximum daily temperatures are also projected to become more variable between seasons in most wheat growing areas globally (Figures S9B and S9D). Mean precipitation changes are spatially diverse (Figure S9E) over wheat growing seasons. The variability in precipitation tends to increase under 2°C global warming (Figure S9F). These features of projected temperature and precipitation change are in line with multi-model CMIP5 projections that formed the basis of IPCC's AR5 report.[46]

The APSIM-Wheat model simulates the grid-based wheat yield under the grid-specific cultivar, soil, irrigation, and fertilizer model setting. We aggregated the grid-based yield simulations to the country scale. By forcing the model with climate data from the MERRA2, the APSIM-Wheat model generally reproduces the interannual variability of global wheat-yield dynamics over 1990–2016 (Figure S2C, compared with FAO data[44]). The model can simulate the heterogeneous country-specific year-to-year differences in absolute wheat yields (Figure S10) with a median bias of 7.2%. Such a mode performance falls within the range (0%–10%) of previous regional crop model simulations.[2] Moreover, as a secondary check, we also forced the APSIM-Wheat model with the EC-Earth-simulated climate variables and compared the results with those of a wheat model inter-comparison study[2] (Figure S3). Our simulations are very close to the median wheat-yield change and within the uncertainties from various climate models, crop models, parameterization strategies, and management inputs under 2°C warming in Xiong et al.[2] (Figure S3A). The simulations also agree with the results when considering both climatic forcing and CO_2 fertilization under 2°C warming in Xiong et al.[2] (Figure S3B), showing a positive CO_2 fertilization effect that offsets harmful warming impact on wheat in a quantitative manner. Therefore, we believe our model result is a good representation and is comparable with other climate-crop combinations.

Finally, we validate simulated economic results from the GRACE model. Figure S2D shows the interannual exported-weighted average global consumer price of wheat from the FAO database[44] and the GRACE model driven by the historical wheat production in each socioeconomic region. It needs to be stressed that our model approach can simulate price responses induced only by yield variability, but the actual wheat price fluctuation is also influenced by many socioeconomic factors (e.g., oil price, tariffs, and import and export policies). Despite such caveats, the GRACE model generally reproduces wheat price fluctuations at the global scale.

Together, these validation results provide confidence in the model chain and the realism of the experimental outputs.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.oneear.2022.07.004.

ACKNOWLEDGMENTS

We appreciate the anonymous reviewers, editor, and M.S. Xiaoqiang Wang for their kind help and support. This work was jointly funded by the National Key Research and Development Project of China (2019YFA0607402), the National Natural Science Foundation of China (41661144006), the Netherlands Organization of Scientific Research (ALWCL.2016.2), and the European Union Horizon 2020 project (820712). We also acknowledge support from the Youth Innovation Promotion Association of Chinese Academy of Sciences (2018104) and the 2115 Talent Development Program of China Agricultural University. The work is the output of JPI-Belmont Forum "High Impact Weather Events in Eurazia: Selected, Simulated, Storified" (HIWAVES3).

AUTHOR CONTRIBUTIONS

Conceptualization, T.Z. and F.S.; methodology, T.Z., K.v.d.W., and T.W.; investigation, T.Z., K.v.d.W., T.W., J.S., and B.Z.; writing – original draft, T.Z. and K.v.d.W.; writing – review & editing, J.S., X. Yue, R.B., W.A., S.G., and Y.L.; resources, B.Z., R.B., X.C., and X. Yue; funding acquisition, T.Z., F.S., and X. Yang; supervision, T.Z.

DECLARATION OF INTERESTS

The authors declare no competing interests.

Received: December 9, 2021
Revised: June 8, 2022
Accepted: July 21, 2022
Published: August 19, 2022

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