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ORIGINAL PAPER

Role of market agents in mitigating the climate change effects on food economy

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Abstract

Agriculture's ability to adapt to the impacts of climate change is critical for agricultural households as well as the general public and policymakers. Economic agents can play a vital role in adapting to climate disasters. We use a global computable general economic model (GTAP) to assess the role of the domestic market and international trade in mitigating agriculure production losses due to climate change, taking barley as an example. Our results suggest that under the worst-case scenario of extreme events, the domestic and international market imperfections would cause the losses in domestic supply for barley importers to increase by 3.5% and 0.6%, respectively. We conclude that policies aimed at integrating the markets can also effectively act as adaptation measures for climate change.

Keywords Climate change · Natural hazards · Agriculture · Economy · CGE · Market agents

1 Introduction

In addition to the growing population and increasing incomes, climate change is considered as another significant challenge to the future global food security. According to current estimates, in most agricultural regions, the increased radiative forcing will increase earth's surface temperature by around 0.3–0.4 °C per decade to 2050 (IPCC 2013). The growth in agricultural productivity will be severely damaged by these increases in temperature (Nelson et al. 2014a). Moreover, extreme weather disasters have the potential to partially or wholly damage crop production.

The adaptation of agricultural and market systems will determine, to a great extent, the size of damage caused by these climate change on food security of the nations. Farmers,

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traders, and businesses in agriculture and economies at large depend critically on the speedy and accurate information they receive from smoothly working markets, which they use for adaptation to new conditions. On the other hand, assessing the consequences of climate change on agricultural production to the highest accuracy possible is essential for designing effective climate adaptation policies in the agriculture area. That, in turn, requires the knowledge of both physical and economic effects of climate change on agricultural production under different Representative Concentration Pathways (RCPs).

There is an expanding body of fine literature studying the impacts of climate change on agriculture. These studies indicate that crop yields would be negatively affected by climate change (Lobell et al. 2011; Wheeler and Von Braun 2013; Rosenzweig et al. 2014). Most of these studies have only used field experiments or crop models to assess the physical impacts of climate change. Recently, some studies have turned their focus to the economic impacts of climate change on food security, such as Nelson et al. (2014a). However, these studies seldom consider the different contribution of free and restricted markets in alleviating the impacts of climate change (Reilly and Hohmann 1993; Ciscar et al. 2011; Brown et al. 2017).

Weather-related disasters decrease crop yields through various biological processes. In the wake of a disaster, there is little option for farmers to expand their crop area. Both of these factors contribute to reduced production, which in turn result in higher crop prices. These price changes affect the farmers' decisions on land allocation to various crops and crop management in the subsequent season, mostly to counter production losses. Free and fully functional markets are the main prerequisite for the price information to reach the farmers. On the contrary, if the markets have some interventions or the trade is restricted, farmers may not experience accurate price signals in the wake of a disaster, and when the new disaster strikes, they may not be able to react most efficiently.

Additionally, previous studies have often focused on the impacts of the slowly changing climate on agricultural production, such as the average changes in temperature and precipitation in the future. However, climate change increases the frequency and severity of extreme weather events, such as extreme heat and drought (Meehl et al. 2000; Cheng et al. 2012), which threaten global food production more seriously. Already, several extreme weather disasters have caused considerable damages to regional crop production in recent years (Battisti and Naylor 2009; World Food Programme 2010; Gu et al. 2008; Barriopedro et al. 2011; Coumou and Rahmstorf 2012). Unfortunately, the impacts of extreme weather events on cropping systems are seldom quantified, as their rare occurrence makes it hard to be adequately calibrated and tested (Field et al. 2014).

We have designed this study to fill this vital gap in the literature by assessing the impacts of extreme weather events on global grain production and analyzing the role of the domestic market and global trade in ameliorating these effects. Considering that this study focuses on the unique role of market and trade, a specific crop—barley (also with limited case studies)—is taken as an example. Analyzing the impacts of climate change and the role of markets on a single crop have the benefits of avoiding the interaction effects between different crops that might result from a general analysis of climate change on all the crops. This analysis also makes it easier to discern the contributions from different setups in the domestic market and international trade rather than from the changing comparative advantage between different crops due to climate change. Moreover, although we take barley as the focus crop, the implications of this study are also valid for other crops that are affected by extreme events.

Before moving to the next section, we present a short discussion on some key concepts related to adaptation. Figure 1 (reproduced from Antle and Capalbo 2010) shows the net expected economic value of an agricultural production system τ_A at a given location, conditional on the current climate γ_1 as a function of management decisions, x. The management decisions denote the application of variable inputs like seeds, fertilizer, irrigation, energy and labor within a given production system or technology. Both the location and shape of the curve would change under a new the production system τ_B, making the new value function $V(x, \tau_B, \gamma_1)$ (dotted line) flatter than the one for production system τ_A (broad solid line). This production system is not observed at this particular location under the initial climate system, γ_1 because it yields lower maximum value at its apex than the existing system.

In the wake of climate change, we observe a new expected net value function $V[x, \tau_A, \gamma_1]$ at this particular location with its unique agroecological conditions. In the short run, technology is fixed at τ_A. If the producers persist with original management decisions x_A, under the existing technology τ_A, they suffer a significant drop in the expected value of production under the new climate (show be lower apex point of the narrow line curve). The loss would be equal to the vertical distance between points A and B'. The producers can, however, deflate the losses by adopting better management decisions within technology τ_A. At the new management decisions x_B, the adverse climate impact is equal to AB', and the gain from adaptation is BB'.

Now we consider the long run where the producers can make use of alternative technologies. Some of those alternate technologies, like cropping systems or crop varieties, might be available but with lower maximum profits, τ_B (shown by the dotted line curve in Fig. 1). The maximum point C, of this curve, is much lower than A under the current climate conditions. However, under the extreme weather conditions, technology τ_B yields a value function which remains unaltered under climate change. Since C is better than B, the producers of this region prefer this technology under climate change. We see that when due to simultaneous adjustments in management and technology, the loss due to climate change is significantly reduced (vertical distance between A and C).

As discussed in Antle and Capalbo (2010), depending upon the involvement of government and private business and the technology, there are three sets of adaptation. The first set of adaptations—typically involving managerial decisions by farmers and

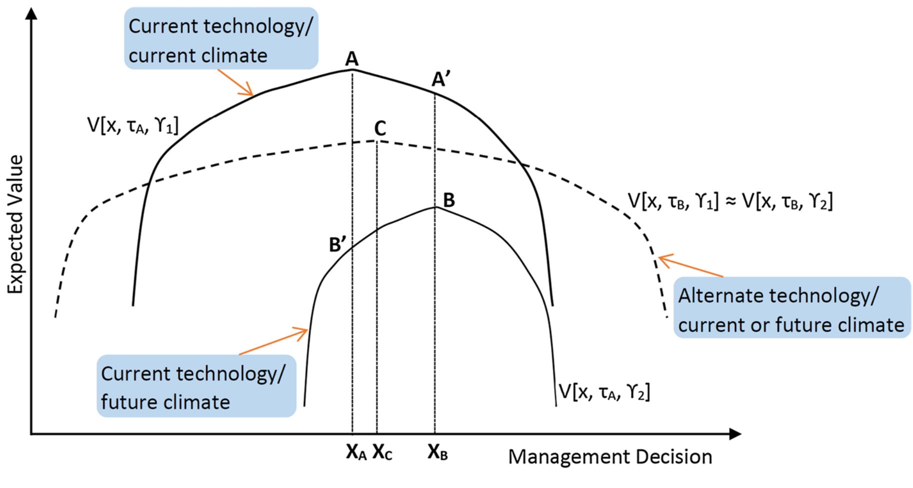

Fig. 1 Adaptation to climate change based on existing and new technologies. Source: Antle and Capalbo (2010) (Fig. 3)

agribusinesses—is based on current technology and can be attained in a shorter period and do not require major new investments. The second set of adaptation involves the adoption of a new technology, which can be a new technology or an existing technology with lower profits under the old climate. The third set of adaptation involves the institutional environment within which the producer is operating. This encompasses government policies, publicly available information, as well as the functioning of input and product markets.

The literature also distinguishes the adaptations (discussed above) into the ones termed as autonomous and planned adaptations. The autonomous adaptations are based on processes that are caused by the normal market. The first set of adaptations falls into the autonomous category, where the farmers react to climate change by changing their managerial decisions. Intrinsically, the autonomous adaptations are highly dependent on the market structure that relay the price information to the farmers. The planned adaptations, on the other hand, are related to government investments, policies, or institutional reforms. The second set of adaptations is more likely to be the result of a mix of public and private actions. Moreover, the third and final set of adaptation—markets and policy—is much more likely to be the result of planned adaptation. By the same token, poor planning can also result in underachievement of the adaptation targets or even totally miss these targets (Hertel and Lobell 2014).

2 Methods

For analyzing the role of the domestic market and international trade in times of weather disasters, we use a global economic model (global trade analysis project model, GTAP) to assess the impacts of extreme drought and extreme heat disasters on the domestic supply of barley under different scenarios. Here, the domestic supply indicates the domestic production minus net import. Assessing the climate change effects needs two sets of data, (1) on climate data and (2) data on physical yields changes due to climate change. Specifically, the climate data pertain to the disaster events under different RCP scenarios during 2011 to 2100, and the corresponding data on temperature and precipitation during the barley-growing season, which are based on Earth System Models (ESMs). In this study, we only present the analysis under of RCP 2.6 (termed as upper bound) and RCP 8.5 (termed as lower bound), for simplicity.

The crop model (DSSAT) provides the physical change of barley yield, based on the climate data under disaster scenarios. In the end, these yield changes are used in the GTAP model as shocks to simulate the impacts on the domestic supply of barley and the role of domestic market and trade on barley supply around the globe. Below, we describe the above methods in more detail.

2.1 Selection of disaster events

Disasters events are the primary mechanisms by which climate damages crop production (Lobell et al. 2013; Lesk et al. 2016). In this study, we define disaster events as the global drought and heat extremes (more severe than 100-year events) that occur concurrently during the barley-growing season around the globe. We focus on the extreme weather events (unlike the slow climate change) as it is not easy to predict in which particular year will they strike and also because many of the adaptation measures are unable to cope with them. Below we outline the detailed steps of selecting disaster events over during 2010–2100:

We start with calculating the global barley drought and heat disaster threshold values corresponding to 1 in 100-year probability in historical data (1981–2010). For this, we estimate standard precipitation index (SPI ≤ − 1.0) and extreme degree days 30 °C + (EDD) for each grid in all barley planting regions during the barley growth period (spring and winter barley) from 1981–2010. We adopt a weighted average method to calculate annual global drought and extreme heat index. Then, we fit the annual global barley drought and heat indices with Pearson-III distributions and use the fitted curves to derive the global barley drought index and heat index corresponding to 1-in-100-year probability. This gives us the global barley drought and heat disaster threshold values. The threshold (30 °C) is consistent with the existing literature, which shows that exposure to temperatures over 30 °C is harmful to barley growth (Sakata et al. 2000; Abiko et al. 2005; Oshino et al. 2007). The annual global barley drought index is calculated using standardized precipitation index (SPI) when SPI value is less than − 1 (Mckee et al. 1993).

In the next step, we use barley drought and heat disaster threshold values to select concurrent global drought and heat waves in a year in the future under climate change as projected by five different global climate models. In this study, we include the results from 5 ECMs, i.e., GFDL-ESM2 M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, and NorESM1-M, to account for the uncertainty between the ESM models. The disaster years are categorized as the years when both extreme drought and extreme heat concurrently strike in the same growing season of the same year globally. All modeled disaster years are selected to simulate global barley yield using the process-based crop model. Here, we identify 17 disaster years under the upper bound RCP 2.6 and 139 disaster years under the lower bound RCP 8.5. Once again, both RCP 2.6 and RCP 8.5 are termed as upper and lower bounds as they are expected to produce the lowest and highest yield losses, respectively.

2.2 Estimation of physical yield change

Based on the disaster years selected above, we simulate global barley yield change due to disasters on a gridded level by the CSM-CERES-Barley module, which is part of the Decision Support System for Agrotechnology Transfer (DSSAT) version 4.6 (Hoogenboom et al. 2015). The gridded formatted inputs used to drive the DSSAT model include daily weather data, soil parameters, crop calendar data and management information. Specifically, we used the following process in the DSSAT model:

First, we model barley yields across the world during the historical period, i.e., 1981–2010. Barley yield is simulated at 0.5° × 0.5° grid scale, with two main production systems (spring barley and winter barley) and two water management scenarios (fully irrigated and rainfed). Historical national barley production is aggregated from simulated gridded yield and weighted by grid cell barley areas around the year 2000 from the gridded global dataset by combining two data products of Monfreda et al. (2008) and Spatial Production Allocation Model (You et al. 2009).

Then, we tune and calibrate model parameters related to crop genotype characteristics so that the simulated yields from 1981 to 2010 were comparable to the statistical data. Next, barley yields across the world are simulated during disaster years under 5 ESMs and 2 RCPs. In the next step, global and national yields are aggregated from gridded values.

Table 1 Biophysical effects of increased temperature and drought on plants. *Source*: * From Hertel and Lobell (2014). # From Farooq et al. (2009)

Response to heightened	
Temperature*	Drought#
Faster development; shortened grain-filling stage leading to reduced yields; can boost yields when water stress occurs at the end of the season	Impaired germination and poor stand establishment (Harris et al. 2002).
Warming can either increase or decrease net carbon uptake depending on crop type, starting temperature and day/nighttime warming; higher temperatures increase vapor pressure deficit (VPD) which leads to water stress	Lower cell growth due to loss of turgor pressure. Impaired mitosis, cell elongation, and expansion result in reduced plant height, leaf area and crop growth under drought
Heightened VPD leads to higher soil evaporation and plant transpiration and lower soil moisture	Many yield-determining physiological processes in plants respond to water stress
Both cold and hot extremes can damage plant cells; extreme heat during flowering increases sterility	Drought at flowering commonly results in barrenness
Invasive weeds often more climate tolerant; also more responsive to changes in temperature due to short juvenile period, long-distance dispersal; reduced frost frequency will expand range of pests and diseases	Decreasing water availability under drought generally results in limited total nutrient uptake and their diminished tissue concentrations in crop plants

Finally, change in national/regional and global yield is calculated, which is the deviation from the average national/regional or global yield during 1981–2010 (More details on how to apply ESMs and DSSAT model to simulated future barley physical yield change can be found from Xie et al. 2018.)

In Table 1, we also outline briefly the main reasons that climate change affects crop productivity to facilitate the understanding of the scientists working in climate adaptation and integrated assessment modeling.

2.3 Global economic model and scenarios

In the following two subsections, we describe the working of the global economic model (GTAP) and how we designed the economic simulation scenarios for analyzing the effects of extreme weather events on barley supply.

2.3.1 The global economic model

The GTAP is a well-known multi-regional computable general equilibrium model, which is widely used in assessing the impacts of climate change and policy changes (Hertel et al. 2010; Bosello et al. 2012; Golub et al. 2013). The model is based on the assumptions that producers minimize their production costs, and consumers maximize their utilities subject to a set of certain common constraints. Supply and demand of all commodities balance out through price adjustments in perfectly competitive markets. Representative consumers of each country or region are modeled as having a non-homothetic Constant Difference of Elasticity (CDE) demand function. On the production side, firms combine intermediate inputs and primary factors (e.g., land, labor, and capital) to produce commodities with constant-return-to-scale technology. Intermediate inputs are composites of domestic and foreign components, with the foreign component differentiated by region of origin (the Armington assumption).

In this study, we use the latest GTAP database version 9 (with the base year of 2011). The standard GTAP database contains 140 countries/regions and 57 sectors. The original GTAP database barley crop is part of a bigger sector "other grain," containing several grain crops. We split barley from "other grains" based on the data on barley production and use (FAO 2017) and commodity trade data (DESA/UNSD 2017). Finally, we aggregate the GTAP database into 18 sectors while ensuring that all the competing and complimenting sectors for barley are present in the most disaggregated form (see Table 2 in the Appendix). At the same time, we aggregate the GTAP regions into 33 regions while keeping the detailed representation of all the main barley-producing, consuming, and trading regions (see Table 3 in the Appendix).

The yield shocks for barley were incorporated into the GTAP model via changes in land use efficiency for the land used by barley in each region (parameter "afe" in Eqs. 1 and 2). This is the conventional method for translating yield perturbations into economic models (Nelson et al. 2014a, b; Iglesias et al. 2012). Land use efficiency affects both price and demand for land in the following two equations. In addition to the land use efficiency parameters, we also make changes to land substitution parameters among different crops and the substitution of land and other inputs (labor, capital, and others) from their original values of GTAP database to represent the disaster situation.

The equation of price of primary factor composite in each sector/region (the following equations are in percentage form, same hereafter) is as follows:

$$\mathrm{pva}_{j,r} = \sum_{k=1}^{n} \left(\mathrm{SVA}_{k,j,r} \times \left(\mathrm{pfe}_{k,j,r} - \mathrm{afe}_{k,j,r}\right)\right) \tag{1}$$

where j production commodity (industry), r region, k endowment commodity, *pva* firms' price of value added in industry j of region r, *pfe* firms' price for endowment commodity k in ind. j, region r, *SVA* share of k in total value added in j in r, *afe* sector/region-specific average rate of primary factor k augmenting technology change.

Endowment commodities' input to each region/industry is as follows:

$$\mathrm{qfe}_{k,j,r} = -\,\mathrm{afe}_{k,j,r} + \mathrm{qva}_{j,r} - \mathrm{ESUBVA}_{j} \times \left(\mathrm{pfe}_{k,j,r} - \mathrm{afe}_{k,j,r} - \mathrm{pva}_{j,r}\right) \tag{2}$$

where *qfe* demand for endowment k for use in industry j in region r, *qva* value added in industry j of region r, *ESUBVA* elasticity of substitution between capital/labor/land, in production of value added in j.

2.3.2 Scenarios for GTAP simulations

To assess the economic impacts of extreme weather events on global grain production and identify the contribution of the domestic market and global trade, we constructed three types of simulation scenarios. In the first scenario, we assume that climate change affects all the countries in the world under such a situation that the values of land substitution parameters among different crops and the substitution of land and other inputs (labor, capital, and others) are set to 10% of their respective original values in the GTAP database. The lowering of these parameter values reflects the difficulty the farmers will face in the time of disaster and is a common approach in economic modeling of climate change effects (e.g., Rose and Liao 2005; Rose et al. 2007).

Under the second scenario, we use the same yield shocks as in the first scenario, but we introduce domestic market imperfection, which allows the price signals to reach slowly and inaccurately to the farmers such that they show little or no reaction to the increased domestic prices of barley. In modeling terms, this is achieved by lowering the ease of land substitution between different crops and also the ease of substitution of land with other inputs.

Under the third scenario, we incorporate import tariffs on barley imports by all the world regions to showcase the impact of imperfect international markets. Specifically, on top of the second scenario, we add a 20% uniform import tariff on barley in all the countries. Comparing the results of the latter two scenarios with the first scenario would reveal the role of the domestic market and global trade in buffering the impacts of extreme weather events. For the analysis, we divide the countries/regions into two groups, i.e., net importers and net exporters of barley.

3 Results analysis

3.1 Physical yield loss of barley

Among the 450 modeled years of each RCP (2011–2100 projections in each of the five ESM models), we identify 17 and 139 disaster events with 100-year extremes of drought and heat under RCP 2.6 and RCP 8.5, respectively. Here, the disaster event refers to a global extreme event rather than the certain region (s) experiencing the disaster (the reality is that some regions experience severe losses, some regions experience light losses while some regions experience positive impacts). In other words, we select the disaster event using the global average disaster severity index, rather than for some specific countries. We then model barley yields changes in 34 world regions (most of which are individual countries) when the world experience 100-year extreme disasters using the process-based crop model (DSSAT). The average barley yield changes due to disasters under 5 ESM models during 2011–2100 for each region are shown in Fig. 2.

Most countries would experience barley yield loss under both RCP scenarios, with the yield losses under RCP 8.5 much higher than those under RCP 2.6. For example, under RCP 8.5, Denmark and Estonia have barley yield decline by over 45% due to extreme weather events. Most of the other countries/regions have barley yield loss between 10 and 30% due to the disasters. However, under RCP 8.5 scenario, five regions also experience an increase in barley yield, with Romania seeing a yield increase of around 15%. Under RCP 2.6, Denmark faces the most severe yield losses by around 35%. Most of the other countries/regions have barley yield loss of less than 20%. In contrast, ten regions have barley yield increase, and among them, Romania has the biggest yield increase by about 28%. Interestingly, as the biggest barley importer, the yield loss in China is lower than the global average level. The barley yield in China increases by 2.7% under RCP 2.6 and declines by 12.05% under RCP 8.5, respectively. Australia, the biggest exporter of barley, would have yield loss more severe than the global average under RCP 8.5 (25.77% for RCP 8.5; 2.25% for RCP 2.6).

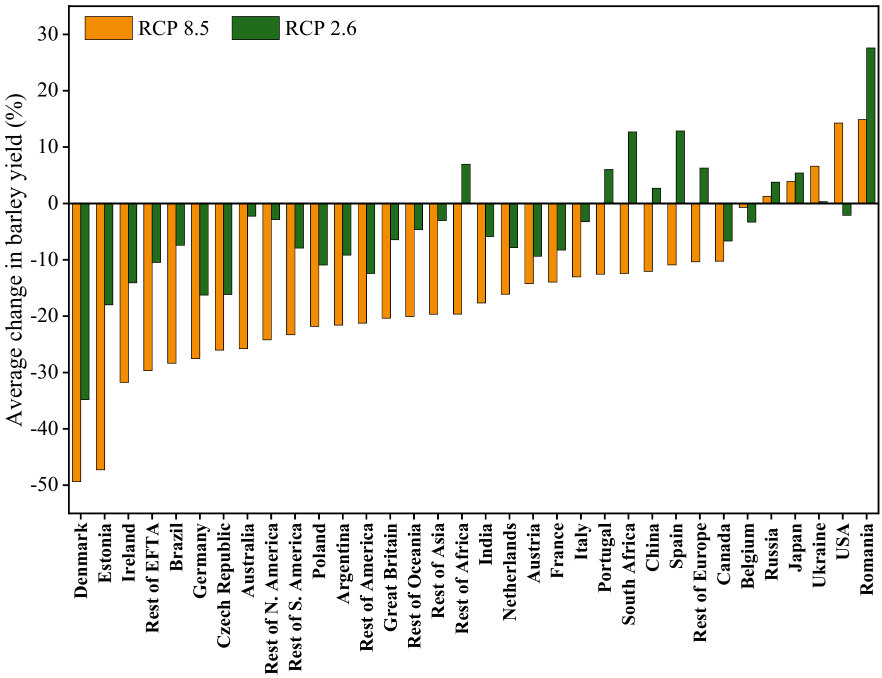

Fig. 2 Average impacts of extreme weather events on barley yield for each region during 2011–2100 under RCP 2.6 and RCP 8.5 (%). Source: Crop simulation model

3.2 Impacts of domestic market imperfections on barley supply under climate change

For the first set of GTAP scenarios, we simulate the impacts of extreme weather events on barley production using barley yield changes across the globe. We take these simulations as the baseline to compare the role of the domestic market and international grade in buffering climate change impacts on barley importers and exporters. Under each run of the simulations, we feed one disaster event shock (barley yield change) for all the countries/regions into the GTAP model. This gives us 17 simulation results under RCP 2.6 and 139 simulation results under RCP 8.5 for all the countries/regions, respectively. To save space, we only present average changes under 5 ESMs during 2011–2100 in the following analysis (see the full range of results regarding changes in domestic barley supply for net importers and net exporters under both RCP 8.5 and RCP 2.6 in Fig. 5 in the Appendix).

Under the first set of scenarios, the extreme weather events would reduce barley supply in both barley importers and barley exporters under RCP 8.5. The barley supply for net importers and net exporters would decline by 8.7% and 11.9% under RCP 8.5, respectively (Fig. 3). Under RCP 2.6, the reductions in barley supply would be much lower, i.e., an increase of 0.13% for net importers and a decrease of 0.65% for net exporters. This is because extreme events affect barley yield more seriously under RCP 8.5 than under RCP 2.6.

We know that under the extreme weather events, the farmers would react to changing prices in the domestic market and would try to maintain the barley production to a certain level by improving their field management, such as intensifying labor use, irrigation, and

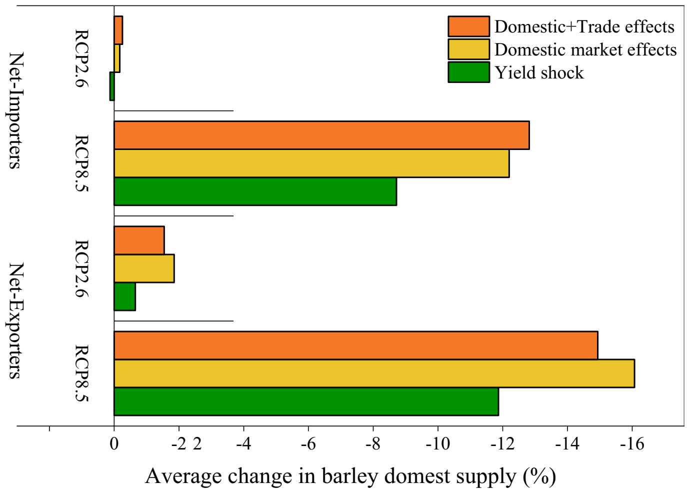

Fig. 3 Impacts of extreme weather events on barley supply of net importers and net exporters of barley (%). Source: GTAP simulation

pesticide application. However, the farmers can only react most efficiently if the market system allows the price signals to reach the farmers speedily and accurately. Under the second set of scenarios, due to the imperfect domestic market, the farmers are unable to size up the price changes accurately. Thus, we see that the supply losses under the second set of scenarios are higher than the supply losses under the first set of scenarios. Specifically, under RCP 8.5 the net importers of barely would face a supply loss of 12.2% (29% higher than the loss under the first scenario), while the net exporters of barley would face a supply loss of 16% (26% higher than the loss under the first scenario) (Fig. 3). For RCP 2.6, the losses (gains) in domestic supply under the second set of scenarios are also higher (less) than the ones under the first set of scenarios (Fig. 3). Thus, we see that in the presence of domestic market imperfections, the farmers significantly lose their ability to cope with extreme events, which otherwise might act as an adaptation measure.

3.3 Impacts of international trade imperfections on barley supply under climate change

In the third set of GTAP scenarios, on top of the parameter settings and yield shocks in the second set of scenarios, we add a uniform 20% import tariff on barley by all the countries/regions to estimate the role of imperfections in international trade on barley supply under climate change. Here, we feed one disaster event shock (barley yield change) for all regions into GTAP model every time, and thus, we get 17 and 139 simulation results for all countries under RCP 2.6 and RCP 8.5, respectively. Once again, for the space consideration, we only present average changes under 5 ESMs during 2011–2100 for net importers and net exporters of barley in the following analysis.

Figure 3 shows that in the presence of an additional 20% import tariff, the domestic supply of barley would change differently for barley net imports and net exporters. As the import tariff would increase the import price and thus decrease the ability of net-importing countries/

regions to import barley, the supply losses for these countries under this set of scenarios would be higher than the losses under the second set of scenarios. Specifically, the domestic supply of barley in net importers would increase by 5% (from 12.2 to 12.82%). This shows that in the presence of imperfections or segmentation—in the form of import tariff, export taxes or non-tariff barriers—the climate change would hit the net-importing countries/regions even harder while removing these imperfections/segmentation in the international trade would naturally act as a buffer to climate change effects on crop supply.

In case of net exporters of barley, (1) as they are at the receiving end of the import tariffs from the imports, and (2) for many of these countries/regions, the yield losses are either quite small or even positive, their domestic supply loss would be smaller under the third set of scenarios than the loss under the second set of scenarios. As shown in Fig. 3, the domestic supply loss for net exporters of barley would reduce from 16% under the second set of scenarios to about 15% under the third set of scenarios. The results follow a similar direction but smaller magnitudes for the net importers and net exporters under RCP 2.6.

From the above results, we can see that the removal of market imperfections from both the domestic market and from the global trade would benefit the countries that are more negatively affected by extreme weather events. For the countries with lower yield losses or positive yield changes, on the other hand, the changes in their domestic supplies from the extreme weather events follow different paths under the imperfect domestic market and trade restrictions. This signifies that although lower global trade would increase the domestic supplies for these countries (due to lower exports), the removal of domestic market imperfections can also act as an effective adaptation measure against climate change.

The reason is that when considering international trade, farmers expect to improve their management decisions (like increasing inputs) to expand production and increase the export to other countries to gain more incomes. Although during the disaster, the international trade rules are predefined, from a long-run view, if the trade is restricted, the disaster is far less likely to increase the price to a general level, and farmers will not move to anew management decision (increase inputs to an optimal level) to avoid losses in the new disaster.

Figure 4 also shows that for most of the net-barley-importing countries/regions the combined distortion in the domestic market and international trade (green bars) contributes more losses in domestic supply than the distortions in the domestic market (blue bars) while the reverse is true for most of the net-barley-exporting countries. For the domestic market response, the increase in production mainly depends on the countries' ability to increase inputs to production and their preference for the affected crop, i.e., barley. It is noted that for different countries the production loss can be different, even if they experience the same barley yield change. For international trade response, disaster, an external shock, changes the comparative advantage of planting barley for different countries. If we have integrated international markets, for the countries with slight yield loss or positive yield change, they usually try to increase input to expand export and gain profit according to their experience. For the severely hit countries, if they want to increase input to satisfy export demand, the loss outweighs the gains.

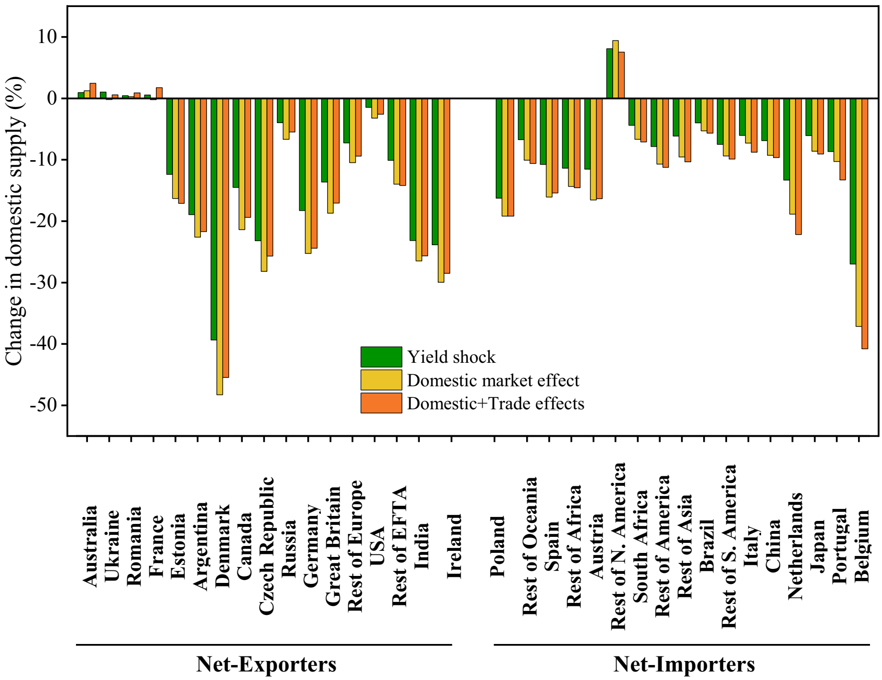

Fig. 4 Comparison of changes in domestic supply of barley in different sets of GTAP simulation scenarios under RCP 8.5

4 Conclusions

Climate change, particularly extreme weather disasters, is considered as one of the main factors affecting future agricultural systems across the globe. More and more studies are recognizing that the severity and intensity of such extreme events will be rising in the future under the worsening climate change. The impacts of extreme weather events induced by climate change on grains (measured in terms of changes in domestic supply or production) are usually measured by natural scientists using crop models or field experiments. However, these methods offer little or no consideration of adaptation measures taken by different economic agents, like producers, traders, and agribusinesses. Consequently, the results from such methods on the impacts of disasters on crops could be misleading as they tend to ignore the broader range of adaptive capacity of agricultural and economic.

In this study, we take barley as an example and use GTAP model (a global economic model) to encompass the response of market agents and to assess the economic impacts of extreme drought and heat on crop supply and analyze the contribution of the domestic market and international trade in diffusing the effects of such extreme events. For this, we start with selecting disaster events based on the results from Earth System Models and derive the barley yield changes for 34 key countries/regions using process-based crop model arising from the most extreme drought and heat events under two Representative Concentration Pathways, i.e., RCP 8.5 and RCP 2.6. Then, we use GTAP model to simulate how crop production changes after perceiving barley yield losses (due to extreme weather disasters);

how imperfections in the domestic market would hinder the price signals and thus affect the domestic supply of the crop; and how the introduction of a distortions in the international trade (import tariff on barley) would affect each country/region's domestic supply through the changes in trade volume in the face of changing comparative advantage.

Our results demonstrate that the domestic supply of barley for the net importers and net exporters of barley would decline differently under the extreme weather disasters. The changes in domestic supply for most of the countries/regions are much smaller than the corresponding physical yield changes. However, after introducing domestic market distortions, we find that negative impacts of extreme weather disasters would further increase for both net importers and net exporters of barley. Further, the distortions in international trade would increase the domestic supply losses for the net importers and reduce these losses for the net exporters. Moreover, for most of the net-barley-importing countries/regions, the combined distortions in the domestic market and international trade contribute more losses in domestic supply than the distortions in the domestic market alone. For most of the net exporters, the relative losses are higher under the distortions in the domestic market.

In times of disaster, market agents like farmers, traders, and agribusinesses change their behavior to cope with the disaster. For example, in the short run, as the production technology is given, the farmers usually change their management decisions by tweaking agronomic inputs like labor, irrigation, and pesticide application to adapt to climate change on their own. The traders of the disaster-hit commodity also change their trading practices to counter the effects the extreme weather disaster. However, in the presence of distortions, barriers, or imperfections in the domestic market and international trade, the price signals will not reflect the true nature of market conditions. This prevents the farmers and traders from learning effectively from the markets that are hit by the disaster.

Moreover, when a new disaster hits the crop, these market agents will not be able to show their most efficient response. Farmers, for example, will not be able to improve their management decisions as much they can to prevent production losses as they were unable to register the correct price signals during the previous disaster. This failure to respond by farmers will (1) further aggravate the domestic supply losses of net imports due to higher losses in domestic output; (2) have ripple effects from the net exporters as the farmers in these countries would not be able to produce more to satisfy the demand from the net importers. On the contrary, if the markets are free of distortions and the trade is unrestricted, farmers will be better able to experience the general price change during previous disasters, and when new a disaster occurs, they may show their adaptation more effectively.

In light of the above results, we conclude that when the domestic market and international trade are kept free of distortions/imperfections, they can also act as effective adaptation measures against climate change and disasters. In order to buffer the impact of disasters on food supply, it is necessary to give full play to the role of market mechanisms and to reduce government intervention in the domestic market and global trade. Efficient and distortion-free market systems are thus recognized as an additional adaptation measure against climate change. The climate change policies should pay due attention to all possible adaption measures, including the free market mechanism. Although this study takes barley as an example, the policy implications apply to other crops as well.

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Appendix

(See Fig. 5, Tables 2 and 3).

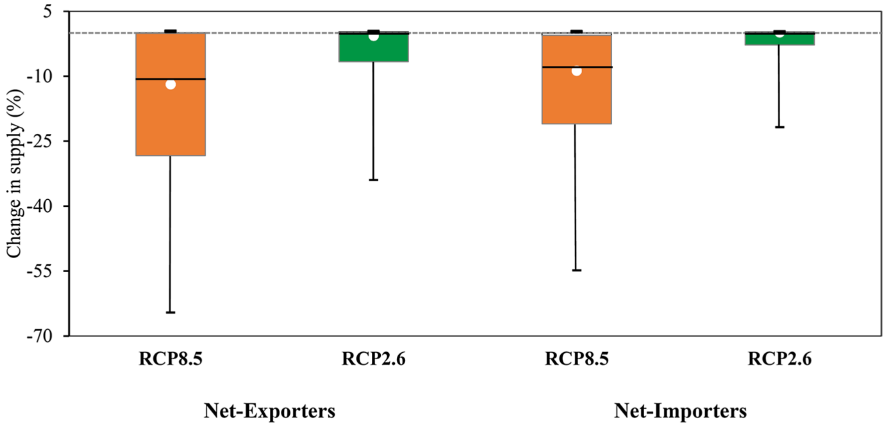

Fig. 5 Range of changes in domestic supply of barley for net importers and net exporters due to extreme weather disasters under RCP 8.5 and RCP 2.6. (Top and bottom of the boxes are 25th and 75th percentiles, the circle is average, and the centerline is the median of the data. Two whiskers indicate the minimum and maximum of all data—$n = 17$, and 139 of extreme events in RCP 2.6 and RCP 8.5, respectively)

Table 2 Sectoral aggregation scheme

Aggregated sectors	GTAP original sectors
Barley	Split from the original "other grains" sector
Beer	Split from the original "beverage and tobacco" sector
Trade	Trade
Recreational services	Recreational services
Other beverage and tobacco	Beverage and tobacco after splitting out beer
Wheat	Wheat
Other grains	Cereal grains nec after splitting out barely
Rice	Paddy rice; processed rice
Edible oils	Oilseeds; vegetable oils and fats
Cotton	Plant-based fibers
Other agriculture	Sugar cane, sugar beet; vegetables, fruit, nuts; crops nec; forestry;
Livestock	Bovine cattle, sheep and goats, horses; animal products nec; raw milk; wool, silkworm cocoons; fishing; bovine meat products; meat products nec; dairy products;
Processed food	Sugar; food products nec
Energy	Coal; oil; gas; petroleum, coal products; electricity; gas manufacture, distribution
Extraction	Minerals nec; mineral products nec; ferrous metals; metals nec; metal products
Light manufacturing	Textile; wearing apparel; leather products; wood products; paper products, publishing; chemical, rubber, plastic products; motor vehicles and parts; manufactures nec

Table 2 (continued)

Aggregated sectors	GTAP original sectors
Heavy manufacturing	Transport equipment nec; electronic equipment; machinery and equipment nec
Transportation and communication	Transport nec; water transport; air transport; communication
Other services	Water; construction; financial services nec; insurance; business services nec; public administration, defense, education, health; dwellings

Table 3 Regions aggregation scheme

Aggregated regions	GTAP original regions
Australia	Australia
Rest of Oceania	New Zealand, Rest of Oceania
China	China
Japan	Japan
Rest of Asia	Hong Kong, South Korea, Mongolia, Taiwan, Republic of China, Rest of East Asia, Brunei Darussalam, Cambodia, Indonesia, Laos, Malaysia, Philippines, Singapore, Thailand, Vietnam, Rest of Southeast Asia, Bangladesh, Nepal, Pakistan, Sri Lanka, Rest of South Asia, Kazakhstan, Kyrgyzstan, Rest of Former Soviet Union, Armenia, Azerbaijan, Georgia, Bahrain, Iran, Israel, Jordan, Kuwait, Oman, Qatar, Saudi Arabia, Turkey, United Arab Emirates, Rest of Western Asia
India	India
Canada	Canada
USA	United States of America
Rest of North America	Mexico, Rest of North America
Argentina	Argentina
Brazil	Brazil
Rest of South America	Bolivia, Chile, Colombia, Ecuador, Paraguay, Peru, Uruguay, Venezuela, Rest of South America
Rest of America	Costa Rica, Guatemala, Honduras, Nicaragua, Panama, El Salvador, Rest of Central America, Dominican Republic, Jamaica, Puerto Rico, Trinidad and Tobago, Caribbean
Austria	Austria
Belgium	Belgium
Czech Republic	Czech Republic
Denmark	Denmark
Estonia	Estonia
France	France
Germany	Germany
Ireland	Ireland
Italy	Italy
Netherlands	Netherlands
Poland	Poland
Portugal	Portugal
Spain	Spain
Great Britain	Great Britain

Table 3 (continued)

Aggregated regions	GTAP original regions
Rest of EFTA	Cyprus, Finland, Greece, Hungary, Latvia, Lithuania, Luxembourg, Malta, Slovakia, Slovenia, Sweden, Switzerland, Norway, Rest of EFTA
Romania	Romania
Russian	Russian Federation
Ukraine	Ukraine
Rest of Europe	Albania, Bulgaria, Belarus, Croatia, Rest of Eastern Europe, Rest of Europe
South Africa	South Africa
Rest of Africa	Egypt, Morocco, Tunisia, Rest of North Africa, Benin, Burkina Faso, Cameroon, Cote d Ivoire, Ghana, Guinea, Nigeria, Senegal, Togo, Rest of Western Africa, Central Africa, South Central Africa, Ethiopia, Kenya, Madagascar, Malawi, Mauritius, Mozambique, Rwanda, Tanzania, Uganda, Zambia, Zimbabwe, Rest of Eastern Africa, Botswana, Namibia, Rest of South African Customs Union, Rest of the World

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