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ARTICLE

The impact of climate change on global food supply and demand, food prices, and land use

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Abstract Climate change induced crop yield change affects food production of countries to varying degrees, depending on the location of the farming activities. Differentiated yield changes of crops may lead to reallocation of agricultural land among uses. Key food exporters may reshuffle due to diverse climate change impact on crop farming among countries. We use a multi-region, multi-sector computable general equilibrium (CGE) model, which considers crop suitability of land in the optimal reallocation decision of land between uses, to simulate the impact on global food production, prices, and land use of crop yield change due to climate change as projected under the IPCC SRES scenario A2. Our findings show that developing countries are more adversely affected by climate change than developed countries. Developed countries are mostly located in higher latitudes, and climate change benefits the crop yield of these areas. In contrast, developing countries of the lower latitudes suffer from the reduction in crop yield being induced by climate change. Considering the fast growing population in the developing world, developed countries are expected to serve as the world's key food exporters by 2020 should the climate change occurs as scenario A2 indicates.

Keywords Computable general equilibrium model · Agro-ecological zone · Land use · Climate change · Food supply · Food demand

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Abbreviations

CGE	Computable general equilibrium
GTAP	Global trade analysis project
AEZ	Agro-ecological zone
GCM	General circulation model
SRES	Special report on emissions scenarios

Introduction

Climate plays an important role in agricultural production. Climate change induced temperature and precipitation changes would affect crop production of countries, the degree of which varies to latitude, topography, and other geographic features of the country. Differences in temperature, soil moisture, soil pH, etc. requirements for crop growth also lead to variations in the production impact of climate change. Researches of the past two decades have been focused on predictions of climate change and its possible impact on agriculture and food supply in the next couple of decades. Lobell et al. (2008) predicts possible global climate change in the next 20 years, which may cause temperature rise and precipitation fall in semi-arid regions, and thus reduction in production of wheat, maize, rice, and other major crops. Brown and Funk (2008) pointed out that reduction in crop production due to the rising trend in food prices since 1990 and the reduction in per capita harvested area have put certain countries deeply in food security problem (FAO 2007). In particular, food security of countries located in tropical and sub-tropical zones is even worse affected by global climate change and the induced global food price fluctuations.

In addition, fast growing economies of large population, like China and India, have contributed to dramatic rise in food demand. As the globalization of agricultural product trade intensifies, climate change impact on food production may affect both food exporting countries and importing countries. Food importing countries are concerned about food security; food exporting countries are concerned about the effect on farm income. Among all the concerns, food price is the common focus. Changes in food prices are determined by both supply and demand: food prices rise when supply falls short of demand, and vice versa. Natural or man-made disasters and income levels are some of the factors that affect food supply and demand.

The purpose of this article is to analyze quantitatively the impact on global food prices of climate change (supply-side impact), with the consideration of changes in food demand due to economic growth (demand-side impact). In order to do so, we use a multi-region, multi-sector computable general equilibrium (CGE) model—the Global Trade Analysis Project (hereafter, GTAP) model (Hertel 1997)—together with the GTAP Version 6 Data Base (Dimaranan 2004) and the newly developed GTAP Land Use Data Base (Lee et al. 2009), which adopted the concept of Agro-Ecological Zoning (AEZ) as developed by FAO (2000) and Fischer et al. (2002). Considering the fact that price-induced adjustments in food production would affect significantly the reallocation of agricultural land among uses (e.g., for either maize or wheat growing), we modified the model so that transition of land between uses is subject to crop suitability of land—which is implied by the terrestrial characteristics and the weather condition at the location of the land. We believe this describes better and more realistically the adjustment of land use, in particular, to climate change.

This article is outlined as follows: we review in "Literature review" section the literature of climate impact on agricultural production and food prices in the long run; we introduce in "The GTAP model and land use change modeling" section the multi-region, multi-sector CGE model, the GTAP model (Hertel 1997), and our modifications in land use modeling; in "Simulation of climate change impact" section, we analyze the simulation results of climate change impact on the region-specific crop production, global food prices, and land use change; "Concluding remark" section concludes this article.

Literature review

Climate change may bring benefits to certain regions, yet damage to other regions. Tol (2002) predicts that a 1°C rise in global mean surface air temperature will bring positive impact on the OECD countries, China, and Middle-East countries, while other countries are negatively affected. Overall impact of climate change on global agriculture by the end of this century is positive. Mendelsohn et al. (2000) use the Global Impact Model (GIM)which includes two climate-response functions, and allows for sectoral adaptationto simulate the possible impact on the product markets of all sectors in all regions of future climate change predicted by two general circulation models (GCMs) under three different scenarios. Their simulations show that the climate change impact varies among countries, and the impact on global agriculture as a whole is positive.

Cline (2007) links the climate change scenarios provided by six GCM models[1] under the scenario A2 of the IPCC Special Report on Emissions Scenarios (SRES) (Nakicenovis and Swart 2000) with two different agriculture impact assessment models—(1) the Ricardian econometric model (Kurukulasuriya et al. 2006; Mendelsohn et al. 1994, 2000, 2001; Mendelsohn and Schlesinger 1999; Reinsborough 2003) and (2) the crop process model (Rosenzweig and Iglesias 2006; Rosenzweig and Parry 1994) to simulate the impact of climate change on all sectors of all regions by end of this century—and finds that climate change impact is mostly beneficial to developed countries. One of the reasons is that developed countries are mostly located in the high latitude areas. Developing countries are mostly negatively affected, among which are Africa, Latin America, and India.

Lobell et al. (2008) links the climate change predictions by 2030 from 20 GCM models and statistical crop models to simulate changes in agricultural production of 12 food insecure regions by 2030. The results show that climate change is likely to cause production of maize—a staple crop in South Asia—to reduce by 30%, and rice, millets, maize—key staple crops in southern Africa—to reduce by 10% if there is not enough adaptation measures. The IPCC Third Assessment Report (IPCC 2001) points out that poor countries (most of them located in tropical and sub-tropical areas) as opposed to rich countries (most of them located in higher latitude areas) will be negatively affected in their agricultural production due to reduction in precipitation and intensified pest problems caused by climate change. Agricultural production in Africa and Latin America—where irrigation infrastructure is insufficient—will be reduced due to temperature rise, and its agricultural productivity may drop dramatically, around 30%, in 100 years.

Darwin (1999) uses the Future Agricultural Resources Model (FARM) (Darwin et al. 1994)—which classifies

[1] The six GCM models are: (1) the ECHAM4/OPYC3 model (Roeckner et al. 1996), (2) the HadCM3 model (Gordon et al. 2000), (3) the CSIRO-Mk2 model (Gordon and O'Farrel 1997), (4) the CGCM2 model (Flato and Boer 2001), (5) the GFDL-R30 model (Knutson et al. 1999), and (6) the CCSR/NIES model (Emori et al. 1999).

land into various categories according to the weather condition where the land is located and the crops for which the land is suitable, and links to the GTAP model (Hertel 1997)—to simulate the responses of all sectors in all regions to climate change and changes in the Ricardian rents. The results of changes in the Ricardian rents show that agriculture of Latin America and Africa are negatively affected, while Russia, located in high latitude area, is positively affected by climate change. The impact on agriculture of Eastern Europe, northern Europe, western Asia, and South Asia appears to be neutral.

Parry et al. (2004) link the climate change scenarios of the next 80 years produced by the HadCM3 model (Gordon et al. 2000) under the IPCC SRES scenarios A1FI, A2, B1, and B2, crop yield changes estimated by crop process models, and the Basic Linked System (BLS)[2] economic model to simulate the impact on cereal grain production and prices and number of people in hunger under the circumstances of climate change, crop yield changes, and economic development. The results show that in the next 80 years, global food supply is sufficient to feed the world under the SRES scenarios. However, the difference in regional impact of climate change on food production looms large by the end of the simulation period. Crop yield changes of developed and developing countries differ most in scenario A2.[3] Developed countries of high latitudes are positively affected by global warming, and thus their crop production will rise in the next 80 years. In contrast, developing countries of low latitudes are negatively affected and need imported foods from developed countries to meet the demand of the large population.

The GTAP model and land use change modeling

We modify the multi-regional CGE model, GTAP (Hertel 1997), to go with the newly developed GTAP land use database (Lee et al. 2009) for the simulation of climate change impact on global food supply, prices, and land use. Such a model and database permits us to incorporate varying land features of agro-ecological zones, with which climatic conditions and terrain properties are considered. The standard GTAP model (Hertel 1997) allows all land-based sectors to compete for land according to relative land rents. However, it does not explicitly identify the suitability and viability of land for growing various crops—model settings like this would produce misleading results concerning the substitutability of land use among the competing sectors. For a country with arable land located under diverse climate and terrain conditions, crop suitability of the land may diverge, and thus land use change among sectors as a whole may be subject to temperature, precipitation, and soil conditions of the location. The AEZ distinction is the key feature of our modeling effort and also contribution to the literature of integrated assessment on climate-change impact.

Agro-ecological zoning

The GTAP land use database (Lee et al. 2009) is compiled following the agro-ecological zoning (AEZ) approach[4]—pioneering work of the Food and Agriculture Organization of the United Nations (FAO) (FAO 2000), and Fischer et al. (2002)—which distinguishes land areas of a region/country by their agro-ecological features. Arable land is classified into agro-ecological zones according to temperature, precipitation, soil type, soil pH, topography, etc. of the location.[5] That is, land areas located in the same agro-ecological zone have similar physical environmental limitations and crop growing potential. The FAO/IIASA AEZ methodology has provided a standard framework for classifying land according to crop suitability (FAO and IIASA 2000). Agro-ecological zoning of land is mainly based on the length of growing period (LGP), which refers to the length of period (or number of days) within a year that the temperature is above 5°C and the soil moisture is sufficient for crop growth (FAO 2000). The LGP also provides a rough measure for crop productivity of the AEZ.

The GTAP land use database

The GTAP land use database (Lee et al. 2009) includes data of land cover, harvested area of crops, area of timber plantation, and production of crops and timber in 18 agro-ecological zones of all countries/regions in the world

[2] The BLS model is a 34-region, 10-sector (nine agricultural, one non-agr.) global computable general equilibrium model for agricultural policies and food systems analyses. Agricultural system is part of the national economy, and is linked with foreign agricultural systems through capital flows and international trade.

[3] As explained in section 3.1 of Parry et al. (2004), crop yields in developed countries under the A2 climate scenario increase due to increases in regional precipitation—which compensate for moderate increases in temperature—as well as the direct effects of high concentration of CO_2. In contrast, precipitation decreases and large temperature increases in developing countries result in huge reduction of crop yields. Complexity in the projected regional patterns of climate variables, CO_2 effects, and agricultural systems are key to the diverse regional projections of crop yields.

[4] The AEZ methodology is developed by the United Nations Food and Agriculture Organization (FAO) and the International Institute for Applied Systems Analysis (IIASA), for evaluating biophysical limitations and agro-ecological potentials of land in various regions, in particular, developing countries.

[5] Irrigation is not accounted for in the AEZ methodology, and, thus, our CGE model of land use considers only the rain-fed conditions of the agro-ecologically zoned land resources.

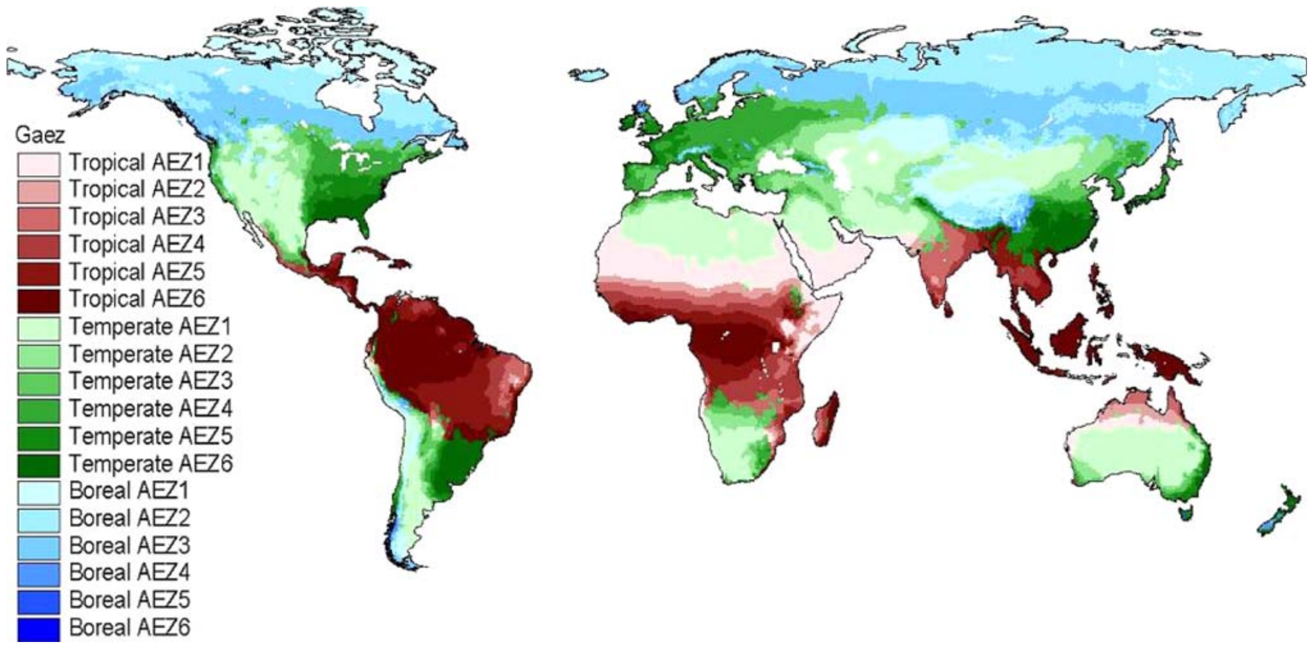

Fig. 1 Global distribution of AEZs. *Source*: Ramankutty et al. (2007)

(Ramankutty et al. 2007; Sohngen and Tennity 2004). The 18 agro-ecological zones are classified by six categories of LGP in three climatic zones (boreal, temperate, and tropical). The six categories of LGP are identified according to the FAO/IIASA AEZ methodology. LGP of AEZ1 is below 60 days a year; LGP of AEZ2 ranges from 61 and 120 days of a year; LGP of AEZ3 is between 121 and 180 days; LGP of AEZ4 is between 181 and 240 days; LGP of AEZ5 ranges between 241 and 300 days; and LGP of AEZ6 is above 300 days a year. Figure 1 shows global distribution of AEZs, at a 0.5 degree latitude by 0.5 degree longitude resolution.

The GTAP land use model

Figure 2 shows the nesting structure for agricultural production in the GTAP land use model. The agricultural sectors include crops sectors (e.g., paddy rice, wheat, other cereal grains, vegetables and fruits, oil seeds, sugar cane and beets, and other crops), and livestock sectors (e.g., cattle, cows, goats, sheep, horses, and other animal products). Under the weak separability assumption, we categorize the inputs to agricultural production as: (A) intermediate inputs and (B) primary factors. We specify a Constant Elasticity of Substitution (CES) function to govern the substitution[6] among labor, land, capital, and natural resources. As such, use ratios between primary factors vary to their relative prices. We assume that all the intermediate inputs are used in proportion to output levels[7]—that is, relative prices of intermediate inputs do not affect their use ratios.

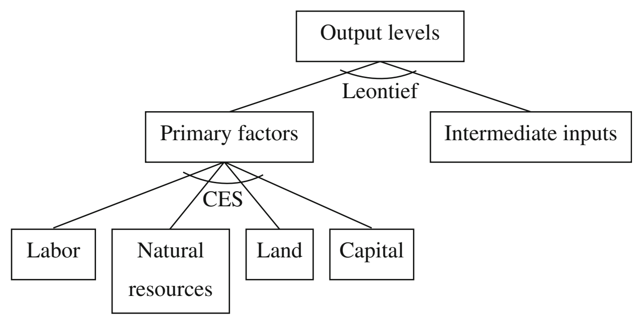

Fig. 2 Production structure of the agricultural sectors

Figure 3 shows the nesting structure of AEZ-specific land demand by the agricultural sectors. We specify a CES function with a large substitution elasticity (of 20) between AEZs, so that land rents of all AEZs, when responding to the exogenous shocks, would change in the same direction and of very similar magnitude. This helps us save data and computation resource requirements in implementing the idea of Lee (2004), in which differentiated production technologies are to be identified for the same crop grown in different AEZs. Since there is not yet good data to support the implementation of the idea of Lee (2004), a large

[6] The specified elasticities of substitution between primary factors vary across sectors. For agricultural and natural resource-based sectors, we specify values ranging from 0.2 to 0.62 and 1.3 for manufacturing and services sectors—which follows the suggestion as in Dimaranan (2004).

[7] In this article, we use "production" and "output levels" interchangeably.

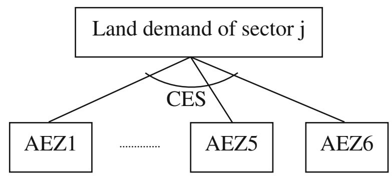

Fig. 3 Nesting structure of sector-specific land demand

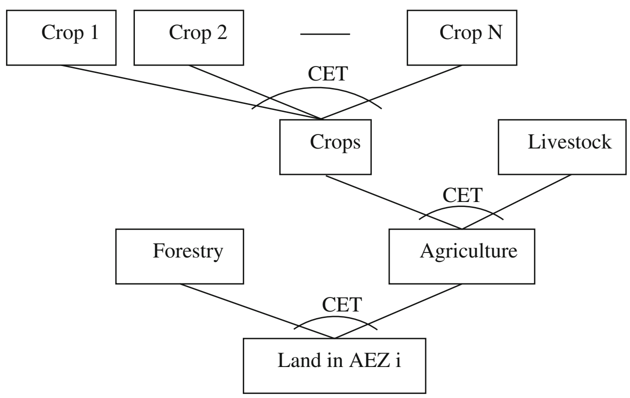

Fig. 4 Nesting structure for AEZ-specific land supply

substitution elasticity CES function would perform similarly to the results of Lee (2004), where production technology of a sector is assumed the same across all AEZs—albeit with differentiated output levels.

Figure 4 shows the three-tier nesting structure of AEZ-specific land supply under the weak separability assumption. For each tier of the nesting, we specify a Constant Elasticity of Transformation (CET) function to govern the optimal allocation of land according to relative land rents payable by the using sectors. The bottom most tier of the nesting structure shows the land in an AEZ is first allocated between agriculture and forestry, following the CET function. The middle tier shows the CET governed allocation of land between livestock husbandry and crop farming activities. The top tier shows the CET governed allocation of land among farming activities of various crops.

Simulation of climate change impact

As Parry et al. (2004) indicates, crop yield changes differ most among regions under the A2 scenario. We attempt to simulate the impact on global food supply, prices, and land use of climate change by 2020[8] under the SRES scenario A2 using the above-introduced model and the database of

[8] Typically, a 10-year time scope is regarded as long-term from economic perspectives, while GCM projections are mostly conducted for at least 50 years ahead. In this article, we choose the year 2020 so that our economic simulations correspond better with the agronomic projections in terms of time frame.

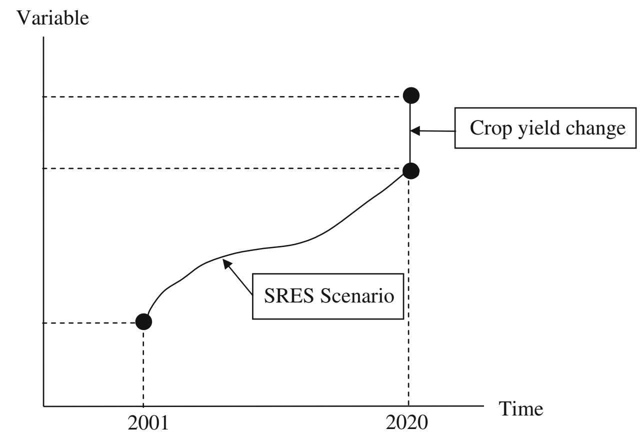

Fig. 5 Simulation design

Lee et al. (2009). Yield changes of three key staple crops—rice, wheat, and coarse grains—as projected by Rosenzweig and Iglesias (2006) are incorporated to present the physical impact of climate change to agriculture. Details of the simulation design are as follows.

Simulation design

Figure 5 illustrates our simulation design, which graphs the values of some variables in our model, say, price of a crop, against time. Our model is a comparative static model. The currently available database for the above-introduced model and the land use database of Lee et al. (2009) is the version 6 of the GTAP database (Dimaranan 2004). The GTAP database is used as the benchmark equilibrium for global CGE simulations—which presents transactions of commodities and services between sectors within and across countries/regions. In order to better simulate the impact of climate-induced crop yield changes by 2020, we first updated the version 6 GTAP database—which shows the global economy in 2001—to present the 2020 benchmark equilibrium, with GDP and population growth forecasts projected by the MESSAGE model (Messner and Strubegger 1995) under scenario A2 of SRES (see Table 1). In order to be consistent with the MESSAGE forecasts of the four world regions (see Table 2), we aggregate the region dimension of our model accordingly. The sector dimension of our model covers 18 producing activities, including key food crops like paddy rice, wheat, and other cereal grains (see Table 3).

Second, we shock the model by the climate-induced crop yield changes of the three key staple crops, i.e., rice, wheat, and coarse grains by 2020 as estimated by Rosenzweig and Iglesias (2006)[9] under the climate change

[9] The benchmark year of Rosenzweig and Iglesias (2006) simulation is 1990.

Table 1 Growth forecasts of GDP and population by the MESSAGE model under scenario A2 of the SRES

	2000	2010	2020
OECD90			
Population (million)	923	975	1027
GDP (ppp[a]) (trillion US$, 1990 prices)	16.0	18.5	20.8
REF			
Population (million)	421	438	454
GDP (ppp) (trillion US$, 1990 prices)	2.6	3.2	4.2
ASIA			
Population (million)	3295	3801	4308
GDP (ppp) (trillion US$, 1990 prices)	7.4	10.3	14.3
ALM			
Population (million)	1530	1974	2417
GDP (ppp) (trillion US$, 1990 prices)	5.2	7.7	11.2

Source: IPCC (2000)

[a] PPP stands for "Purchasing Power Parity"

Table 2 Regions in the model

Regions	Geographical coverage
OECD90	North America
	Western Europe
	Pacific OECD
REF	Central and Eastern Europe
	Newly independent states of the former Soviet Union
	Sub-Saharan Africa
ASIA	Centrally planned Asia and China
	South Asia
	Other Pacific Asia
ALM	Middle East and North Africa
	Latin America and the Caribbean

Table 3 Sectors in the model

No.	Sectors	No.	Sectors
1	Paddy rice	10	Processed foods
2	Wheat	11	Coal
3	Other cereal grains	12	Oil
4	Vegetables and fruits	13	Gas
5	Oilseeds	14	Electricity
6	Sugar cane and beets	15	Other manufacture
7	Other crops	16	Margins service
8	Livestock	17	Other services
9	Forestry	18	Other mining activities

projected by the HadCM3 model (Gordon et al. 2000; Pope et al. 2000). We aggregate the crop yield change estimates of all countries/regions by Rosenzweig and Iglesias (2006)

Table 4 Crop yield changes estimated by Rosenzweig and Iglesias (2006)

Unit: % change	2020		
Regions	Rice	Wheat	Coarse grains
OECD90	+3	+5	−5
REF	−12	−12	−12
ASIA	−1	+3	−6
ALM	−16	−15	−3

Table 5 Climate impact on crop production in all regions under scenario A2 by 2020

Unit: % change	OECD90	REF	ASIA	ALM
Rice	2.2841	−0.7877	−0.3193	−4.7934
Wheat	6.9159	−5.127	1.3775	−8.4768
Other cereal grains	−0.0364	−0.8379	−1.3818	0.2917
Vegetable and fruits	−0.2046	−0.4473	−0.0312	−0.2331
Oilseeds	−0.4313	−0.4574	0.1939	0.1278
Sugar cane and beets	0.0164	−0.3609	−0.1237	−0.1883
Other crops	−0.223	−0.5425	0.288	−0.0189
Livestock	−0.0589	−0.7217	−0.057	−0.2037
Forestry	−0.1534	−0.1076	−0.0757	−0.0383
Processed foods	0.0248	−0.5368	−0.2124	−0.2262

into the four world regions—corresponding to the regions as indicated in Table 2—using regional production shares as weights. The shocks of crop yield changes in the simulations are listed in Table 4. All endogenous variables in our model—including prices and output levels of crops—will respond to such shocks and reach a new equilibrium. We then compare the new and the old equilibria to calculate the impact of the climate change by 2020 on global food supply, prices, and land use.

Analysis of simulation results

Table 5 shows the climate impact on crop production in all regions through crop yield change under scenario A2 by 2020. Climate change brings positive impact on rice and wheat production in the OECD90 region—by an increase of 2.3 and 6.9%, respectively. In contrast, the ALM region is negatively affected, with a 4.8% fall in rice production and an 8.5% reduction in wheat production. Wheat production in the REF region also reduces by 5.1%, while the ASIA region sees a slight increase of 1.4%. Production of other cereal grains in the ASIA region falls by 1.38%. Linking the results of Table 5 with the shocks of physical crop yield changes as listed in Table 4, we can see, in Fig. 6, the relativity of production change among regions conforms to the regional pattern of physical crop yield changes. As we only shock the yield changes of rice,

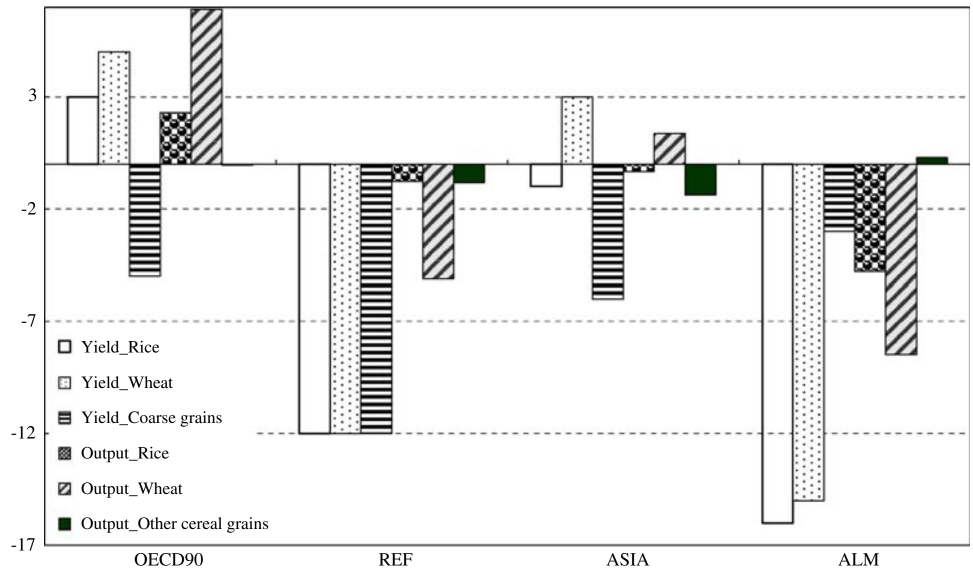

Fig. 6 Regional pattern of production changes and physical crop yield changes under scenario A2

Table 6 Climate impact on unit cost of crop production in all regions under scenario A2 by 2020

Unit: % change	OECD90	REF	ASIA	ALM
Rice	0.3399	7.906	1.638	12.9891
Wheat	1.4786	7.6191	−2.3401	6.7734
Other cereal grains	5.1795	7.4923	8.0585	3.8253
Vegetable and fruits	0.9191	1.2726	0.24	0.6728
Oilseeds	1.0517	1.1413	0.4794	0.7528
Sugar cane and beets	0.978	0.6601	0.1583	0.5392
Other crops	0.8964	0.9133	0.5421	0.6982
Livestock	0.7127	1.4964	0.0993	0.353
Forestry	−0.0813	−0.3444	−0.1631	−0.2138
Processed foods	0.1491	0.659	0.4482	0.3818

Table 7 Climate impact on FOB export prices of crops in all regions under scenario A2 by 2020

Unit: % change	OECD90	REF	ASIA	ALM
Rice	0.3399	7.906	1.638	12.9891
Wheat	1.4786	7.6191	−2.3401	6.7734
Other cereal grains	5.1795	7.4923	8.0585	3.8253
Vegetable and fruits	0.9191	1.2726	0.24	0.6728
Oilseeds	1.0517	1.1413	0.4794	0.7528
Sugar cane and beets	0.978	0.6601	0.1583	0.5392
Other crops	0.8964	0.9133	0.5421	0.6982
Livestock	0.7127	1.4964	0.0993	0.353
Forestry	−0.0813	−0.3444	−0.1631	−0.2138
Processed foods	0.1491	0.659	0.4482	0.3818

wheat, and cereal grains in this simulation, production of other agricultural sectors falls due to the fact that land is competed away by those food crop sectors with positive physical crop yield change.

From Table 6, we see that the unit cost of rice and wheat production in ALM and REF increases considerably—more than 6%. The increase in unit cost mainly results from the rise in land rent. Crop yields of ALM and REF are adversely affected, and as such production of rice, wheat, and other cereal grains are shifted to other regions—that is, ALM and REF import these crops from other regions that are relatively less adversely affected by climate change. Reduction in the demand for land would raise the marginal productivity of land, as we assume diminishing productivity of land in the model. For OECD90 and ASIA, land rents of the rice, wheat, and other cereal grains sectors rise less than that in REF and ALM. This can be explained by the production expansion of these sectors in OECD90 and ASIA, which would require more land, and, therefore, pull down marginal productivity of land, and, thus, land rent.

The cost squeeze is also reflected on the Free-On-Board (hereafter, FOB) prices of exports (see Table 7).[10] The world prices of rice, wheat, and other cereal grains exports rise by 3, 2.56, and 6.07%, respectively. When compared with the world prices of exports[11] (see Table 8), it makes sense to see dramatic reduction in these crop exports of ALM and REF (more than 20% in magnitude, as shown in Table 9). The unit cost of rice production (and thus FOB price) in OECD90 and ASIA rises by 0.34 and 1.64%, respectively, which is much less than the world average

[10] We do not shock export tax rates, so the percentage change in the FOB price will be the same as the percentage change in the unit cost of production.

[11] The percentage change in the world price of an exported commodity is calculated as the FOB-based export value share weighted average of percentage changes in the FOB price of the commodity being exported by all regions.

Table 8 Climate impact on world prices of crop exports under scenario A2 by 2020

Unit: % change	World price of crop exports
Rice	3.0126
Wheat	2.5582
Other cereal grains	6.0682
Vegetable and fruits	0.5709
Oilseeds	0.7505
Sugar cane and beets	0.4609
Other crops	0.7985
Livestock	0.5491
Forestry	−0.1743
Processed foods	0.2793

Table 9 Climate impact on crop exports in all regions under scenario A2 by 2020

Unit: % change	OECD90	REF	ASIA	ALM
Rice	14.5929	−20.5833	21.7313	−49.5972
Wheat	11.2891	−28.077	43.1329	−21.8889
Other cereal grains	0.0144	−4.6448	−4.0968	3.2805
Vegetable and fruits	−0.2841	−1.1769	1.3124	0.5279
Oilseeds	−0.8201	−0.8253	1.8778	0.5791
Sugar cane and beets	0.3863	−0.3174	1.2122	0.0477
Other crops	−0.5356	−0.5949	1.4922	0.7229
Livestock	−0.4694	−2.613	1.7851	1.0408
Forestry	−0.4284	0.7122	−0.1409	0.1729
Processed foods	0.4072	−1.6423	−0.7537	−0.5378

price (3.01%). OECD90 becomes a key exporter of food crops under the climate change impact, with its exports of rice and wheat increase by 14.6 and 11.29%, respectively. ASIA's rice and wheat exports increase much more than those of OECD90—by 21.73 and 43.13%, respectively. Exports of other cereal grains by ASIA fall by 4.1% as its FOB price rises more than the world price. ALM sees a 3.28% increase in other cereal grains exports with its exports relatively cheaper than the world average.

With crop production fall and unit cost rise (more than in other regions), REF and ALM would have to import more crops to meet the domestic demand. This is shown in Table 10. With favorable climate impact on crop yield, OECD90 reduces food crop imports, on top of its significant increase in crop exports.

Table 11 shows changes in AEZ-specific land rent by crop sectors in all regions under scenario A2 by 2020. Table 12 shows corresponding changes in AEZ-specific land demand by each sector of all regions. Land demand by wheat and other cereal grains sectors in OECD90 increases by 1–2% or so. Such increase is to respond to the increase

Table 10 Climate impact on import demand for crops in all regions under scenario A2 by 2020

Unit: % change	OECD90	REF	ASIA	ALM
Rice	−1.8782	12.8275	5.1753	42.0055
Wheat	−1.4314	14.3638	−7.4439	10.1714
Other cereal grains	0.0711	1.2875	1.5457	−1.2587
Vegetable and fruits	0.1426	0.4575	−0.6759	−0.2812
Oilseeds	0.1847	0.0808	−0.6997	−0.5438
Sugar cane and beets	1.083	0.334	−0.6452	−0.2151
Other crops	0.2632	−0.0528	−0.5271	−0.3986
Livestock	−0.013	0.6414	−1.1841	−0.7468
Forestry	0.0932	−0.366	0.008	−0.2421
Processed foods	−0.1714	0.421	0.2735	0.1724

in the demand for OECD90 grain exports by other regions, in particular, the ALM and REF regions—which tend to depend on grain imports from the OECD90 region. Land rents of these two sectors in OECD90 in equilibrium have to rise—by 12.2 and 17.6%, respectively (Table 11)—so as to attract more land into the wheat and other cereal grains sectors. Table 12 indicates that land rent increases of the wheat and other cereal grains sectors attract land in all AEZs from the remaining agricultural sectors. Table 12 also shows that cropland demand in REF and ALM rises due to reduction in crop yield (see Table 4). Land rents of the food crop sectors thus rise in response to the increase in food crop land demand in these two regions.

World prices of food crops rise more than those of nonfood crops. This also contributes to bigger increase in land rents of food crop sectors, which in equilibrium leads to land use change—more land being put into food crop sectors.

Comparing the magnitude of land rent rise among the four regions, ALM and REF—which are worse affected by climate change—see bigger land rent rise, relative to OECD90. Table 11 also shows that all AEZs got very similar magnitude of land rent change. This is the result of our setting in the AEZ-specific land demand.

Table 13 shows regional welfare change in scenario A2 in respond to change in climate-induced crop yield changes. Among the four regions, OECD90 benefits most—with a total welfare increase equivalent to 575.79 million dollars. ALM and REF are the worst hurt regions—with welfare losses equivalent to 2771.92 and 1570.93 million dollars, respectively. When we look into the decomposition of the welfare change, OECD90 gains welfare mostly from the improvement in the terms of trade, while ALM and REF lose welfare mostly due to reductions in crop yields. The improvement of OECD90's terms of trade is mainly the result of increased demand for OECD90's food crop exports.

Table 11 Climate impact on AEZ-specific land rent by crop sectors in all regions under scenario A2 by 2020

Unit: % change	Rice	Wheat	Other cereal grains	Vegetables and fruits	Oilseeds	Sugar cane and beets	Other crops
OECD90							
AEZ1	4.47	12.16	17.58	4.57	4.15	5	4.46
AEZ2	4.48	12.18	17.59	4.58	4.17	5.02	4.47
AEZ3	4.48	12.18	17.59	4.58	4.17	5.01	4.47
AEZ4	4.49	12.18	17.6	4.59	4.18	5.02	4.48
AEZ5	4.48	12.18	17.59	4.58	4.17	5.02	4.47
AEZ6	4.46	12.15	17.56	4.56	4.14	4.99	4.45
REF							
AEZ1	34.96	24.42	35.99	5.97	6.25	6.16	5.71
AEZ2	34.98	24.44	36.01	5.99	6.27	6.17	5.73
AEZ3	34.98	24.44	36.01	5.99	6.27	6.17	5.73
AEZ4	34.99	24.45	36.01	5.99	6.27	6.18	5.73
AEZ5	35.05	24.5	36.07	6.04	6.32	6.23	5.78
AEZ6	35	24.46	36.03	6	6.28	6.19	5.74
ASIA							
AEZ1	2.49	−2.88	12.92	0.69	1.22	0.39	1.52
AEZ2	2.5	−2.88	12.92	0.69	1.23	0.39	1.52
AEZ3	2.5	−2.88	12.92	0.69	1.23	0.39	1.52
AEZ4	2.5	−2.87	12.92	0.69	1.23	0.4	1.52
AEZ5	2.5	−2.87	12.92	0.7	1.23	0.4	1.52
AEZ6	2.5	−2.87	12.93	0.7	1.23	0.4	1.52
ALM							
AEZ1	31.87	15.91	11.27	2.96	3.81	2.98	3.39
AEZ2	31.88	15.92	11.28	2.97	3.82	2.98	3.39
AEZ3	31.88	15.93	11.29	2.97	3.82	2.99	3.4
AEZ4	31.86	15.9	11.26	2.95	3.81	2.97	3.38
AEZ5	31.87	15.91	11.27	2.96	3.81	2.97	3.38
AEZ6	31.87	15.91	11.27	2.96	3.81	2.98	3.39

Concluding remarks

In this article, we attempt to describe in a better and more realistic way the agro-ecological dissimilarities in land characteristics for agricultural purposes in a multi-regional, multi-sectoral CGE model and use it to investigate the implications of regionally diverse impact of climate change. By considering crop suitability of land and region-differentiated yield effects, the framework of our economy-wide impact study in this article provides a new perspective for the global concern on socio-economic consequences of climate change. Our findings are in symphony with those as reviewed in "Literature review" section of this article, in particular, Parry et al. (2004)—methodology of which is closer to ours. Both Parry et al. (2004) and our study show that developing countries are more adversely affected by climate change under the SRES A2 scenario than developed countries. Developed countries are mostly located in higher latitudes, and climate change benefits the crop yield of these areas. In contrast, developing countries of the lower latitudes suffer from the reduction in crop yield being induced by climate change. Considering the fast growing population in the developing world, developed countries may be expected to serve as the world's key food exporters by 2020 should the climate change occurs, as scenario A2 indicates. This suggests that climate change also needs to be taken into account when addressing the issue of poverty elimination inasmuch as developed countries have been playing the role as the major food exporters. For developing countries, efforts may need to be put, in addition to poverty elimination, on the adaptation to climate change in agriculture, so as to raise their productivity and capacity of food production, and hopefully to establish regional balance of food supply.

Table 12 Climate impact on AEZ-specific land demand by crop sectors in all regions under scenario A2 by 2020

Unit: % change	Rice	Wheat	Other cereal grains	Vegetables and fruits	Oilseeds	Sugar cane and beets	Other crops
OECD90							
AEZ1	−0.75	1.03	2.22	−0.73	−0.83	−0.63	−0.76
AEZ2	−1.01	0.77	1.96	−0.99	−1.08	−0.88	−1.01
AEZ3	−0.98	0.8	1.99	−0.95	−1.05	−0.85	−0.98
AEZ4	−1.15	0.62	1.81	−1.13	−1.22	−1.02	−1.15
AEZ5	−0.99	0.78	1.98	−0.97	−1.07	−0.87	−1
AEZ6	−0.54	1.25	2.45	−0.51	−0.61	−0.41	−0.54
REF							
AEZ1	5.14	3.02	5.34	−1.03	−0.97	−0.99	−1.09
AEZ2	4.84	2.73	5.04	−1.31	−1.24	−1.27	−1.37
AEZ3	4.8	2.69	5	−1.35	−1.28	−1.31	−1.41
AEZ4	4.73	2.62	4.93	−1.41	−1.35	−1.37	−1.48
AEZ5	3.8	1.71	3.99	−2.29	−2.23	−2.25	−2.35
AEZ6	4.54	2.43	4.73	−1.6	−1.53	−1.55	−1.66
ASIA							
AEZ1	0.43	−0.91	2.89	−0.02	0.12	−0.09	0.19
AEZ2	0.38	−0.97	2.84	−0.07	0.06	−0.14	0.14
AEZ3	0.38	−0.96	2.84	−0.06	0.07	−0.13	0.14
AEZ4	0.32	−1.02	2.78	−0.13	0.01	−0.2	0.08
AEZ5	0.3	−1.04	2.76	−0.14	−0.01	−0.21	0.06
AEZ6	0.28	−1.06	2.74	−0.16	−0.03	−0.23	0.04
ALM							
AEZ1	5.61	2.26	1.22	−0.72	−0.52	−0.72	−0.62
AEZ2	5.46	2.11	1.07	−0.87	−0.67	−0.87	−0.77
AEZ3	5.37	2.03	0.99	−0.95	−0.75	−0.95	−0.85
AEZ4	5.77	2.41	1.37	−0.58	−0.37	−0.57	−0.47
AEZ5	5.66	2.31	1.27	−0.68	−0.47	−0.68	−0.58
AEZ6	5.6	2.25	1.21	−0.74	−0.53	−0.73	−0.63

Table 13 Regional welfare change with respect to climate-induced crop yield change under scenario A2 by 2020

Unit: million US$	Total welfare change	Welfare change: due to changes in		
Regions		Terms of trade	Crop yield	Allocative effect
OECD90	575.79	1362.72	9.17	−813.74
REF	−1570.93	30.61	−1505.81	−113.36
ASIA	−1332.85	−739.32	−546.95	−197.80
ALM	−2771.92	−653.81	−1769.54	−160.78

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