

The role of international trade in managing food security risks from climate change

Uris Lantz C. Baldos · Thomas W. Hertel

Received: 11 January 2015 / Accepted: 12 February 2015
© Springer Science+Business Media Dordrecht and International Society for Plant Pathology 2015

Abstract International trade plays an important role in facilitating global food security in the face of a changing climate. In considering this issue, it is useful to distinguish between two different time scales: inter-annual and inter-decadal. Inter-annual adjustments in international trade can play an important role in shifting supplies from food surplus regions to regions facing food deficits which emerge as a consequence of extreme weather events, civil strife, and/or other disruptions. The first section of the paper explores the evidence on increased inter-annual supply side volatility, as well as historical and prospective analyses of adaptation to such volatility and the role international trade can play in mitigating the adverse impacts on food security. In the long run, we expect that the fundamental patterns of comparative advantage will be altered by the changing climate as well as availability of technology and endowments (water for irrigation, labor force, capital stock). In a freely functioning global economy, long run trade patterns will respond to this evolving comparative advantage. However, historical food trade has not been free of obstacles, with both tariff and non-tariff barriers often limiting the adjustment of trade to the changing economic landscape. This section of the paper capitalizes on a newly available library of climate impact results in order to characterize the tails (both optimistic and pessimistic) of this distribution. We then explore the potential for a more freely functioning global trading system to deliver improved long run food security in 2050.

Keywords Climate change impacts · Food security · Price volatility · International trade · Climate change adaptation

Introduction

This paper examines the role of international trade in managing the food security risks posed by climate change. We distinguish between two distinct types of risks. The first pertains to the occurrence of extreme weather events. Climate scientists predict that increased concentrations of greenhouse gases (GHGs) in the atmosphere will lead to greater frequency and intensity of extreme heat, as well as precipitation (Diffenbaugh et al. 2005, 2007; IPCC 2013). The ensuing damage to crops from heat waves, drought, and flooding are predicted to be significant (Schlenker and Lobell 2010; Schlenker and Roberts 2009) and are likely to contribute to increased commodity price volatility (Diffenbaugh et al. 2012), which in turn can translate into greater vulnerability of the poor to poverty and malnutrition (Ahmed et al. 2009). Mitigating these risks will require a broad range of adaptations, including increased commodity stockholding, more flexible farming practices and economic policies and increased openness to international trade. However, even with these adaptations in place, it is likely that commodity markets will be more volatile in the future — both due to greater supply-side volatility, as well as due to diminished willingness of wealthier households to curb their volume of food consumption in the face of shortages.

The second type of food security risk posed by climate change is that which results from long run, secular changes in average temperature and precipitation as GHGs accumulate in the atmosphere. As these changes will be gradual, there is greater scope for adaptation, provided that the changes are anticipated and appropriate long term investments can be made (Hertel and Lobell 2014). The IPCC Working Group II foresees that the probability of climate change having “negative impacts on average crop yields becomes likely in the 2030s”, with “median yield impacts from 0 to −2 % per decade over the rest of the century” (IPCC 2014). However,

U. L. C. Baldos (✉) · T. W. Hertel
Department of Agricultural Economics, Purdue University, 403 West
State Street, West Lafayette, IN 47907, USA
e-mail: ubaldos@purdue.edu

these trends in global yields mask considerable variation in the regional impacts of climate change (Rosenzweig et al. 2014), with much of the tropics being hit hard by rising temperatures, while some temperate producing regions are expected to benefit from longer growing seasons. These differential geographic impacts of climate change suggest that international trade will necessarily play an important role in moving crops and livestock products from surplus to deficit regions (Reilly et al. 2002; Tobey et al. 1992).

In this paper, we explore these linkages between climate change, international trade, and food security by drawing on the existing literature, as well as by adding some original analysis of the long run impacts of climate change. In the latter case, we seek to explore the tails of the current distribution of climate impact results. To date, most of the studies of long run climate impacts have focused on ‘most likely’ outcomes. However, the analysis of Hertel et al. (2010) demonstrates that, while the most likely outcomes typically have modest impacts on the poor, the tails of this distribution could have significant consequences — both positive and negative for the world’s food insecure populations. In order to explore this issue in greater depth, we exploit a newly published library of 36,000 climate impact results (Elliott et al. 2014; Rosenzweig et al. 2014; Villoria et al. 2014). From this archive, we take a sample of several of the most extreme combinations of forcings, climate model results, as well as estimated crop impacts, and assess the potential impacts on malnutrition in the developing world by mid-century under alternative international trade regimes.

Food insecurity and extreme inter-annual events

Why this is important Extreme weather events have long been a source of food insecurity. Failure of the annual monsoons to come soon enough, or excessive rainfall in 19th century India was a great source of food insecurity (Burgess and Donaldson 2010). One of the biggest problems in confronting such production shortfalls was the difficulty of transporting large amounts of grain from unaffected, or lightly affected regions to the most severe deficit regions of the country. Indeed, in their study of Indian railroad expansion between 1861 and 1930, Burgess and Donaldson (2010) found that the introduction of railroads led to diminished local price and real income volatility in response to regional productivity shocks. They also found that mortality rates became less sensitive to variation in rainfall following railroad penetration. Clearly trade — be it inter-regional or international — can play an important role in buffering the impacts of heterogeneous weather shocks.

The buffering potential of international trade is likely to become more important in the future, as climate scientists predict that increases in GHG concentrations in the

atmosphere are expected to result in increases in extreme weather events — including more hot, wet and dry extremes (Diffenbaugh et al. 2007; IPCC 2013). Indeed, there is evidence that increases in climate extremes are already occurring (Easterling et al. 2000). This is expected to result in greater damage to crop production (Diffenbaugh et al. 2012; Schmidhuber and Tubiello 2007). While new varieties of crops can aid in adaptation to such changing environmental circumstances (Olmstead and Rhode 2011) such adaptation will take time, and the incentives for adaptation may be muted by the lower yields often associated with more climate-robust crop varieties. Indeed, Lobell et al. (2014) found that the push for higher maize yields in the U.S. has actually resulted in *greater* sensitivity of this crop to drought. Diffenbaugh et al. (2012) found that, in the absence of positive biophysical adaptation, climate change could result in a doubling of the standard deviation of year-on-year U.S. maize price changes. This suggests that other adaptations will be required in order to limit the impact of such supply side shocks on commodity prices and food insecurity.

Household impacts of climate extremes are heterogeneous Before progressing further with an analysis of the impact of food price volatility on food insecurity, it is important to highlight the great heterogeneity of the poor in developing countries. Ahmed et al. (2009) follow the categories developed by Hertel et al. (2009) in breaking households up into seven strata based on their primary source of income. These include: agricultural self-employed, non-agricultural self-employed, urban labor, rural labor, transfer dependent, urban diversified and rural diversified households. The authors analyzed the poverty impacts of a once-in-30 year extreme climate events focusing on prolonged heat waves and dry days as well as excessive precipitation. Their results show that urban, wage labor dependent households are most vulnerable to climate-driven shocks to agricultural productivity. Like all low-income populations, they devote a large share of their income to food consumption. When food prices rise, their real incomes fall sharply and they must cut their consumption of food, thereby worsening food security. On average, poverty rates in this stratum rose by 30 % across the authors’ sample of 15 developing countries in Asia, Africa and Latin America.

In contrast, the agriculture self-employed households are least affected by extreme climate events, with average poverty rates rising by just 9 %, and the estimated poverty rate for this stratum of the population falling in one country (Philippines). This more modest impact is due to the fact that, as crop producers, these households *benefit from higher food prices*. The other strata fall in between these extremes. Diversified households typically obtain some of their income from farming, and rural labor households can either be hurt by adverse climate shocks, or they may benefit from the increased demand for rural labor that ensues following a natural disaster. For

example, Banerjee (2007) found that rural wages rose in the wake of flooding due to the need for replanting which boosted the demand for unskilled rural labor. Ahmed et al. (2009) found that, on average, an additional 250,000 households will be at risk of falling into poverty under future inter-annual weather shocks under end-of-century climate conditions. Increased exposures in Bangladesh and Mexico contribute to the majority of the rise in the number of households at risk of poverty.

Evidence on the historical poverty impact of food price spikes — albeit emanating from a variety of causes (Abbott et al. 2011) — is offered by Ivanic and Martin (2008) who estimated the changes in poverty rates in a sample of 10 developing countries in the light of the food price spikes of 2007/2008. In assessing the rural poverty impacts, they emphasize the adverse impacts on low-income rural producers who are *net buyers* of food products. They found that, while the impacts were heterogeneous — and poverty actually fell in several countries in their sample — overall poverty rates rose by an average of 2.7 percentage points in the wake of these price spikes, with steeper increases in rural areas relative to urban areas.

In general, there are few studies linking extreme events to incomes and nutritional outcomes of the poor. Recognizing that the impact of extreme events will depend both on the impact of food prices on consumption as well as incomes of the poor, we proceed to focus on the impact of climate extremes on commodity price volatility, as this is easier to observe. It is clear that greater volatility in these prices could adversely affect low-income urban households who may spend more than 50 % of their income on food. However, we must continue to bear in mind that the potential impacts on those who are food insecure will be extremely diverse — particularly in light of the heterogeneity in their income sources as discussed above.

Climate extremes and food price volatility In a recent study, Diffenbaugh et al. (2012) explored the consequences of anticipated changes in future temperature and precipitation over the continental U.S. on maize price volatility. They found such price volatility could increase dramatically in the wake of four decades of climate change. This is primarily caused by the adverse yield impacts owing to the increased incidence of excessive heat — temperatures over 29 °C — during critical phases of plant development. Furthermore, they pointed to U.S. biofuels policy as a potential source of further instability, owing to the existence of quantity targets for ethanol use (the Renewable Fuel Standard, or RFS), which are independent of market conditions.

Verma et al. (2014) built on the results of Diffenbaugh et al. (2012) and examined more closely the role of market integration in adaptation to future climate extremes. They found that a key determinant of future responses to such extremes resides

in the manner in which the corn and oil markets are integrated. While binding RFS mandates are very destabilizing, establishing a tighter connection with energy markets could actually be beneficial for adaptation. Verma et al. (2014) recognized that this is a double-edged sword as oil prices are themselves quite unstable and there is a fear of crop commodity markets inheriting this instability. However, the analysis of Verma et al. (2014) suggests that the benefits, which come from having an additional, very large, price-responsive source of demand for grain, dominate the potential costs of being more closely linked to volatile energy markets. They conclude that the most beneficial economic adaptation is market-driven integration with energy. However, this will only occur if oil prices rise beyond recent levels and remain high enough to attract additional investments and allow for expansion of biofuels production.¹

Verma et al. (2014) also examine the impacts of international market integration on commodity price volatility in the context of climate change. In particular, they consider the potential for “free trade” — in this case elimination of import tariffs — to buffer climate shocks. By conducting their stochastic simulation analysis twice — once with tariffs in place and once without — they were able to ascertain the impact of greater market integration on climate-driven commodity market volatility. Not surprisingly, they found that this form of adaptation does indeed reduce price volatility. However, the impact is relatively modest — particularly when compared to inter-sectoral integration with energy noted previously. This finding is influenced by the fact that the authors treated current trade policies (import tariffs and export taxes) as exogenous and unchanging. Therefore, in the tariff-laden scenario, they did not allow tariffs to vary in response to market conditions. Furthermore, they did not consider the possibility of changes in export taxes or other restrictions on exports when world markets spike.

In fact, the political economy of food is such that countries often have a strong incentive to shield urban consumers from world price spikes (Anderson et al. 2013), thereby attempting to avoid the urban unrest which may follow high food prices. Of course, the fewer countries which allow domestic supply and demand to adjust to global scarcity, the greater the adjustment required to equilibrate global supply and demand. Martin and Anderson (2012) and Anderson and Nelgen (2012) used a simplified trade framework to estimate the extent to which national border policy responses to the 2006–2008 food crisis (both export taxes and import tariff reductions) contributed to increased world market price volatility. They found that changes in border restrictions accounted for about two-fifths of the rise in international rice prices, one-fifth of the rise in wheat prices and just 10 % of the rise in

¹ At the time of this writing, oil prices have been falling. However, this may be a transitory phenomenon.

maize prices. Thus, by understating the contribution of trade distortions to current market volatility, the estimates of Verma et al. (2014) would appear also to understate the potential for trade reforms to mitigate future price volatility.

Ahmed et al. (2011) pointed out that government export bans can also limit favorable opportunities created by climate change for some of the world's poorest countries. Those authors studied Tanzania, examining future projections of adverse climate impacts (more specifically, severe dry conditions) on trade, welfare and poverty in that country. Instead of simply studying impacts on Tanzania, the authors also considered potential impacts in her main trading partners, along with the world's major producing regions. They found that many of her trading partners were expected to experience droughts in years in which Tanzania was only mildly affected. This opens the possibility of Tanzania exporting grain in years when the world's major producers are adversely affected by extreme events and world prices are high. However, these are precisely the conditions under which Tanzania has previously imposed export bans! Such bans prevent rural producers from taking advantage of high world prices. It exacerbates the resulting rise in world prices, and it limits the incentive to invest in improved agricultural infrastructure, thereby preventing these opportunities from lifting the incomes of the rural poor.

All of this suggests that, from the point of view of maximizing the value of international trade as a vehicle for mitigating the adverse impacts of extreme events, the most important discipline on international trade is likely to be curtailing the policies aimed at insulating domestic markets from world price developments. However, it is precisely these types of policies which have proven to be the major stumbling block in international trade agreements under the WTO. Many developing countries count such policies as critical to their domestic food security programs, which seek to ensure stable (and low) prices for consumers. At the time of this writing, a temporary resolution has been agreed upon which prohibits challenges to domestic policies as long as it is line with food security objectives (WTO General Council 2014). A comprehensive WTO agreement on the banning of export restrictions remains elusive, although there are opportunities outside this institution wherein voluntary agreements could be reached (Anania 2013). Overall, movement towards more liberal global trading regime remains limited.

The role of international trade in reducing food insecurity in the face of long run climate change

The long run challenge In the long run, the challenge posed by climate change is rather different from that of managing extreme events. On a decadal scale, we expect the fundamental patterns of comparative advantage to change, with

agriculture expanding in regions which are relatively more productive and have lower production costs. This will be driven by a variety of factors, including differing rates of growth in crop productivity, changing variability in environmental factors such as precipitation, temperature and ground water for irrigation, as well as shifting availability of economic endowments including labor force and capital for new investments. In a freely functioning global economy, trade patterns will respond to the evolving comparative advantage. However, food trade has never been free of obstacles, with widespread tariff and non-tariff barriers which limit the responsiveness of global agricultural production to changing economic forces. This section of the paper utilizes the SIMPLE model of global agricultural production, consumption and trade (Baldos and Hertel 2013) in order to explore the long run evolution of regional demand and supply for food, and the potential for achieving improved long run food security in the context of a more tightly integrated global trading system.

The SIMPLE model In contrast to other global models which emphasize temporal, spatial, and sectoral complexity, SIMPLE (a Simplified International Model of agricultural Prices, Land use and the Environment) is designed to be as parsimonious as possible, focusing only on the key drivers and economic responses which govern long run food consumption and production. The model has been validated against history and can faithfully replicate historic changes in crop production, area, yield and prices at global scale (Baldos and Hertel 2013). SIMPLE has also been used to analyze climate change mitigation and adaptation in the agricultural sector (Lobell et al. 2013), the environmental implications of future agricultural productivity growth (Hertel et al. 2014) and the prospects for food security by 2050 (Baldos and Hertel 2014).

The basic framework of SIMPLE is summarized in Fig. 1. Starting with food consumption (top portion, in red), per capita food demand is driven by exogenous per capita income growth and food prices, which are endogenously determined within the model. Food commodities covered in SIMPLE comprise three categories: crops, livestock products and processed foods. Consumer responses to income growth and food prices evolve to reflect shifts in dietary preferences — moving away from crops towards livestock and processed foods. Per capita food consumption is then summed over the entire population to derive total food consumption.

The structure of crop production is illustrated at the bottom portion of Fig. 1 (in green). Crops are produced by combining land and aggregate non-land inputs. The latter input embodies all other factors of production — excluding land — which are used by the crops sector. The non-land input aggregate includes labor, machinery and working capital, pesticides and fertilizers, among other things. SIMPLE has been designed to allow for endogenous changes in crop yields via input substitution between land and non-land inputs. The evolution of

Demand

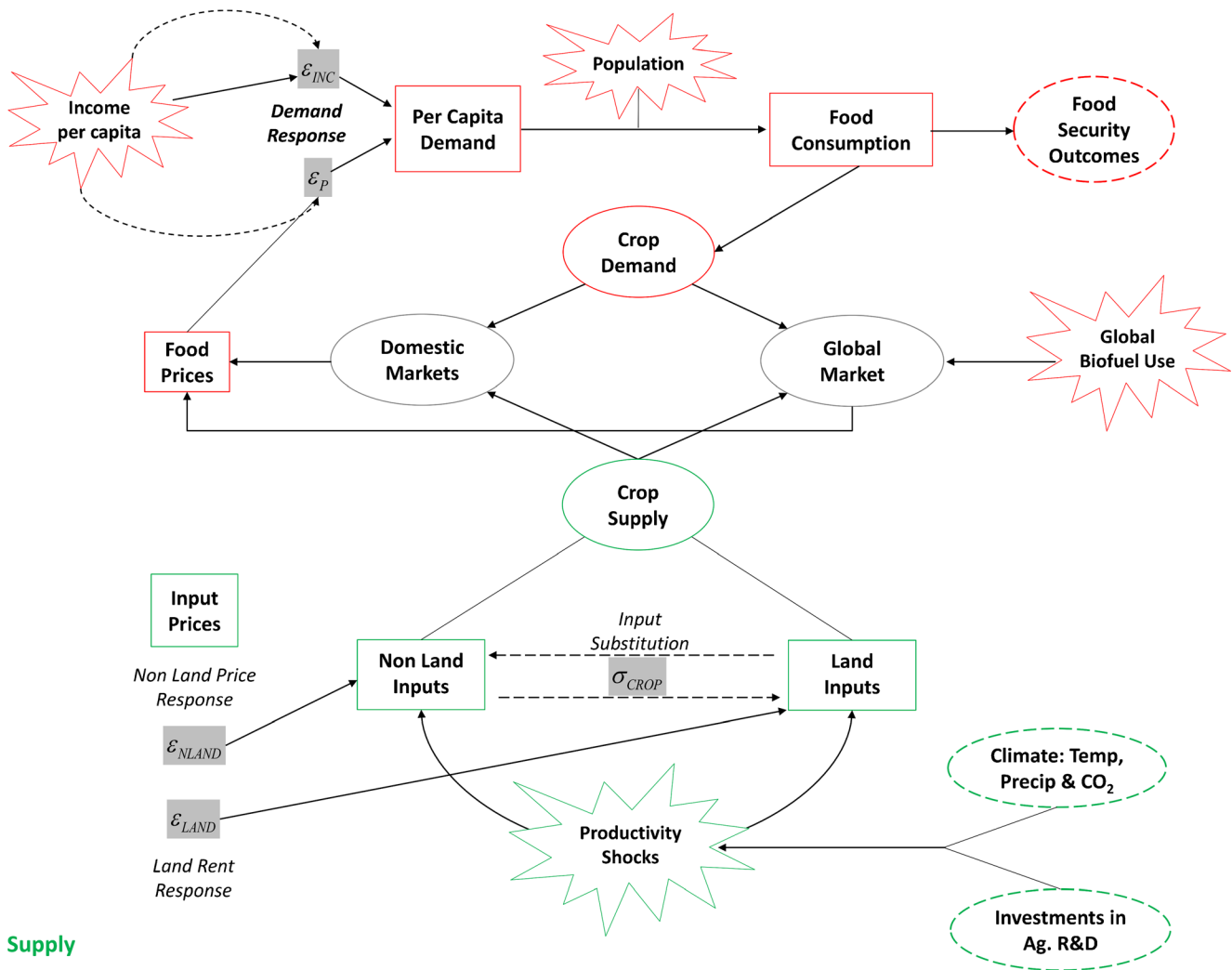


Fig. 1 The SIMPLE model with domestic and global markets

crop yields is also driven by exogenous assumptions about productivity trends due to climate change and/or additional investments in agricultural R&D. Once produced, crops are allocated towards direct food consumption, feed use in the livestock sectors, raw input use in the processed food industries, as well as feedstocks in the global biofuel sector.

National and international markets facilitate interaction among economic agents and determine equilibrium food consumption, production and prices. The presence of tariff and non-tariff trade barriers, as well as other trade costs, diminishes the capacity of markets to respond to prevailing supply and demand conditions. In this paper, the SIMPLE model is modified to examine the consequences of market barriers. Starting with the case wherein trade barriers are present, it is assumed that consumers and producers can participate in either the global or the domestic crop markets (middle portion of Fig. 1). Greater travel time to markets due to large distances and/or poor

infrastructure often increase transaction costs and prevent some economic agents from accessing international markets (Disdier and Head 2008; Limão and Venables 2001). In SIMPLE, this market segmentation is introduced explicitly. Both consumers and producers have imperfect access to international markets so domestic and international prices do not move in lock-step. Of course, in the extreme case wherein crop markets are perfectly integrated, then there is a single global market which determines the global crop price (Baldos and Hertel 2013). We will explore the implications of integrated world markets as well, contrasting the long run impact of climate change in this context with the outcomes in the segmented markets case.

In SIMPLE, changes in food security are driven by changes in average caloric consumption (Baldos and Hertel 2014). Changes in per capita food consumption are directly converted to changes into average caloric

consumption. Furthermore, by characterizing the full distribution of caloric consumption within a region, using the lognormal distribution,² and applying a minimum dietary energy requirement, it is possible to express malnutrition in terms of the average shortfall in caloric consumption amongst the under-nourished population (FAO 2012). However, it is important to note we are only looking at one dimension of hunger and a more robust measure of food security should include adequate consumption of key macro- and micro- nutrients as well as vitamins.

Figure 2 summarizes how changes in per capita caloric consumption are translated into shifts in the distribution of caloric consumption. By way of illustration, Fig. 2 plots the caloric distribution for Sub Saharan Africa in the years 2006 (solid black line) and 2050 (dashed blue line). The vertical dotted line within the 2006 distribution represents the minimum caloric requirement. The area to the left of this line is the fraction of the population which is malnourished, having caloric consumption below the required amount. Going forward to 2050, rising per capita incomes lead to increased food and caloric consumption. Greater caloric intake shifts the distribution, resulting in a thinner tail to the left of the unchanging minimum caloric requirement. The malnutrition incidence in 2050 is the area bounded by the minimum dietary energy requirement and the new caloric distribution curve. Once calculated, the malnutrition index may then be combined with population data to derive the malnutrition headcount within a region. The average depth of malnutrition may also be computed from the new distribution.

Experimental design A series of carefully designed experiments has been developed in this paper to evaluate the range of possible food security changes owing to climate change under different trade regimes. Starting with the baseline scenario, the global farm and food system is projected from 2006 to 2050 in the absence of climate change. Key growth rates used in the forward-looking projections are listed in Table 1. In the coming decades, it is expected that population and per capita incomes will dictate food demand. The population and income growth rates are based on the Shared Socio-economic Pathways (SSP) Database (2013). These SSPs have been specifically designed for climate change impact assessment by providing alternative trends in socio-economic development when climate change impacts are ignored (Kriegler et al. 2012; O'Neill et al. 2014). In this study, SSP 2 is used, which assumes that future socio-economic and

technological development permits successful implementation of climate change adaptation and mitigation strategies (Kriegler et al. 2012). The recent assessments of the potential impacts of climate change on crop yields worldwide, which are used in this study, are also based on SSP 2 projections (Elliott et al. 2014; Müller and Robertson 2014; Nelson et al. 2014; Rosenzweig et al. 2014).

The global growth rates reported in Table 1 suggest that income growth will outpace population growth (0.8 % per annum); thus, per capita income growth (2.4 % per annum) will be a key driver of future food demand. Regions wherein strong per capita income growth is expected include China/Mongolia and South Asia. Note that food consumption in these regions will likely shape global trends as a large share of the world's populace currently reside in these areas. Although population growth is slowing globally, the developing world will still experience steady population growth — particularly in Sub Saharan Africa.

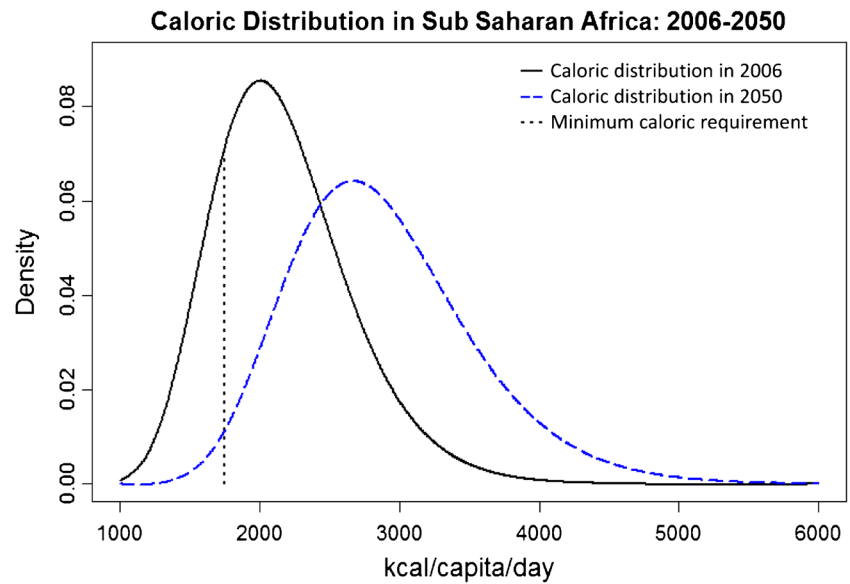
In addition to population and income, future food demand will also be affected by crop feedstock demand for first and second generation biofuel production. Projections of global biofuel consumption is based on the “Current policies” scenario published in the World Energy Outlook (IEA 2008, 2012). These forecasts are based on the results of a detailed world energy model given exogenous growths in GDP and population as well as assumptions on future energy prices and technology. With the “Current policies” scenario, all energy policies for the power and transportation sectors enacted as of mid-2012 are taken into account.

Sustained growth in agricultural productivity is crucial to meet ever-increasing food demands in the coming decades. In this study, estimates of total factor productivity (TFP) growth rates—a measure of productivity which accounts for *total* output given *over-all* input use—are used in future projections. Regional TFP growth rates for the crops and livestock sectors are based on adjusted historical estimates from Fuglie (2012) and projections from Ludena et al. (2007). Lacking detailed TFP projections for the processed food sector, historical rates from Griffith et al. (2004) are used, assuming that these rates apply in the future and across all regions.

Having established the future baseline scenario, the subsequent experiments incorporated crop yield impacts of climate change. Recent projections of food security outcomes based on the SIMPLE model (Baldos and Hertel 2014) used a narrow set of climate change yield shocks generated from a single crop model and averaged across alternative future climate scenarios (Müller et al. 2010). This paper improves on the previous work by capitalizing on a newly available library of climate impact results based on the latest Global Gridded Crop Model (GGCM) inter-comparison project (Elliott et al. 2014; Müller and Robertson 2014; Nelson et al. 2014; Rosenzweig et al. 2014). It provides a comprehensive evaluation of the uncertainties imposed by climate change on future agricultural

² Early work by FAO (Neiken 2003) found that the log-normal distribution has a better fit of household data on caloric consumption compared to other distributions. The log-normal is also widely used in the poverty literature to calculate the poverty headcount and poverty incidence (see Foster et al. (1984)) and similar indices can be constructed to measure the incidence and headcount of caloric undernutrition.

Fig. 2 Distribution of caloric consumption for Sub Saharan Africa in 2006 (*solid black line*) and in 2050 (*dashed blue line*). Within each distribution, the area to the left of the minimum daily caloric consumption (*dotted black line*) is the fraction of the population who are undernourished



productivity. These yield impacts vary across crop, space and time, and also consider the absence/presence of CO₂ fertilization as well as irrigation. The results of the GGCM inter-comparison project are available to the public and can be freely accessed using the AgMIP tool developed by Villoria et al. (2014) (<https://mygeohub.org/tools/agmip>). Climate change productivity shocks are constructed using global yield projections for the 21st century for four rain-fed crops (maize, rice, wheat and soybean), generated under differing assumptions about CO₂ fertilization (present in one case, and

absent in the other). The reason for considering the two extremes for CO₂ fertilization is that there remains considerable uncertainty about the size of these effects (Long et al. 2006). Early studies were undertaken in artificial environments (greenhouses) in which the value of improved water efficiency were potentially overstated. This has led some authors to wholly ignore CO₂ fertilization in assessing the crop impacts of climate change (Nelson et al. 2014). However, we disagree with this approach and believe it is more appropriate to consider these two scenarios as upper and lower bounds on

Table 1 Future growth rates of key drivers

Regions	Population	Per capita income	Biofuel	Total factor productivity		
				Crop	Livestock	Processed food
Eastern Europe	-0.13	3.20		1.33	1.04	
North Africa	1.05	3.07		1.24	-0.30	
Sub Saharan Africa	2.05	3.49		0.63	0.43	
South America	0.73	2.47		1.33	2.64	
Australia/New Zealand	1.23	1.32		0.82	0.42	
European Union+	0.27	1.27		0.95	0.42	
South Asia	1.07	4.17		0.77	1.71	
Central America	0.83	2.02		1.32	2.64	
Southern Africa	0.73	2.62		1.16	0.43	
Southeast Asia	0.80	3.69		1.29	2.38	
Canada/US	0.74	1.17		1.17	0.42	
China/Mongolia	0.07	5.26		1.61	2.38	
Middle East	1.43	2.06		1.02	-0.30	
Japan/Korea	-0.17	1.56		1.29	0.42	
Central Asia	0.67	4.68		1.33	1.04	
World	0.83	2.41	5.80	0.95	2.15	0.89

Data sources from left to right: population and income growth from the Shared Socio-economic Pathways (SSP) Database (2013), World Energy Outlook (IEA 2008, 2012), total factor productivity growth for crops, livestock and processed food sectors from Fuglie (2012), Ludena et al. (2007) and Griffith et al. (2004) respectively

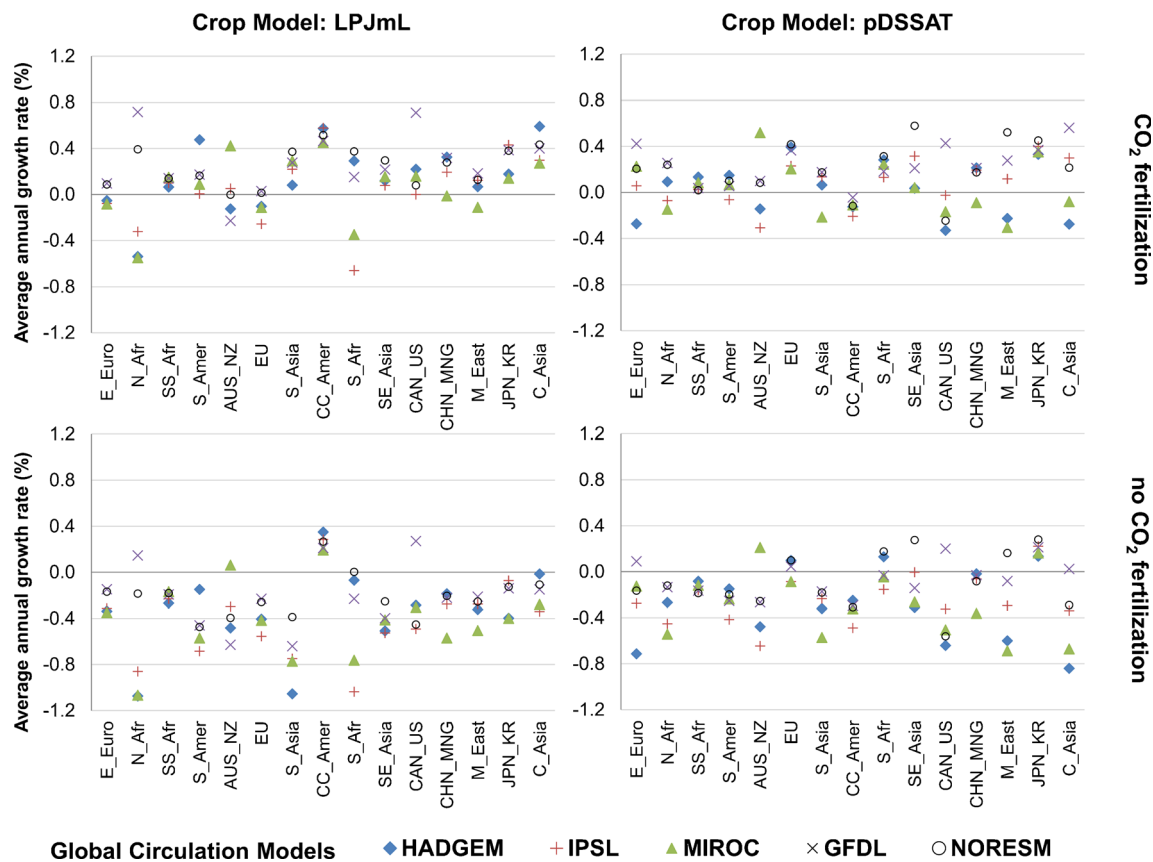


Fig. 3 Changes in crop yields due to climate change with (*top panel*) and without (*bottom panel*) CO₂ fertilization effects (in % per annum over the period, 2006–2050). These are based on aggregated grid-cell level yields

for rain-fed maize, soybean, wheat and rice for each crop model and GCM model combination

climate impacts for any given combination of crop model/SSP/ global circulation model (GCMs).

Available yield projections for most global crop models remain somewhat limited. Given the crop coverage and CO₂ fertilization assumptions covered in this paper, only two global crop models have adequate data for all five GCMs.³ These are the pDSSAT and the LPJmL crop models.⁴ Productivity shocks were calculated given future climate generated using GCMs under the RCP8.5 scenario which assumes that GHG emissions and atmospheric concentrations are expected to rise sharply in the future. Grid-cell yield outcomes were aggregated from the grid cell to each region in the SIMPLE model using gridded crop production data from Monfreda et al. (2008). We then aggregated across all four crops using crop production values from FAOSTAT (2014) to derive the final productivity shocks for each region.

³ These consist of HADGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, GFDL-ESM2M, NorESM1-M. For convenience, these models are mentioned in the paper as HADGEM, IPSL, MIROC, GFDL, NORESM, respectively.

⁴ The EPIC model also has sufficient data but it is not available in the version of the AgMIP tool that we used in this study.

For purposes of assessing the full range of uncertainties in climate impacts, it is important that the two crop models underpinning these estimates derive from the two major families of crop modeling approaches and therefore reflect significant differences in underlying base data and assumptions regarding the expected impacts of climate change on crop yields. The pDSSAT model is a site-based crop model and is calibrated using data from controlled field experiments at specific locations. On the other hand, the LPJmL model is a global ecosystem crop model and therefore relies on production data collected at the level of administrative units such as counties, provinces and countries. These two models also embody differences in the input data on climate and soils as well as on the assumptions regarding fertilizer application rates, crop cultivars and initial level of atmospheric CO₂ (Rosenzweig et al. 2014).

Figure 3 summarizes the crop yield impacts from climate change which are used in the future projections. When CO₂ fertilization effects are considered (*top panel*, Fig. 3), the yield reductions are much lower, relative to the estimated impacts when CO₂ fertilization is ignored (*bottom panel*, Fig. 3). Indeed, crop yields in some regions might even rise in the presence of CO₂ fertilization, based on the current parameterization

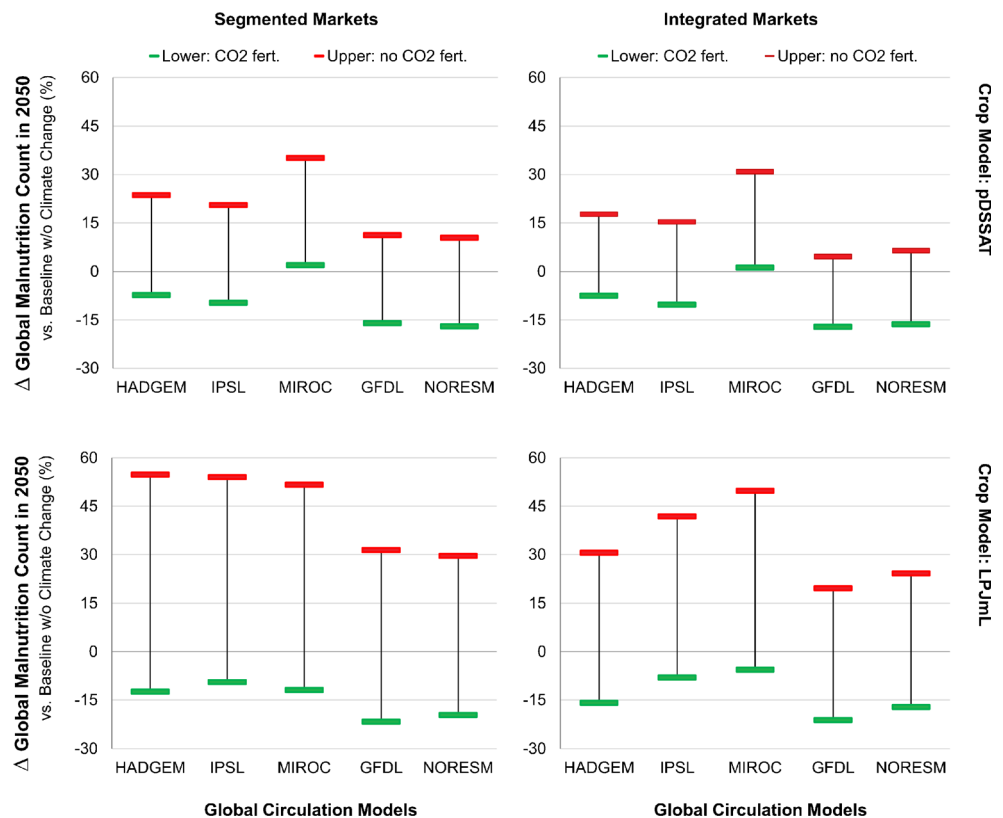
of these crop models. Across crop models, the pDSSAT model (right-hand panels, Fig. 3) generates more conservative estimates of crop yield impacts relative to the LPJmL model (left panels, Fig. 3). If CO₂ fertilization effects are omitted then the expected crop yield reductions from climate change are generally steeper under the LPJmL model (lower left panel, Fig. 3). Looking at the Sub Saharan Africa (SS_Afr) and South Asia (S_Asia), regions which are most vulnerable to food insecurity, the observed reductions in crop yield growth are quite notable under the LPJmL and HADGEM model combination (−1.1 and −0.3 % per annum, respectively). As most of the world's malnourished reside in these regions, we pay special attention to the future food security trends in Sub Saharan Africa and South Asia in the advent of climate change.

Future food security impacts of climate change The global impacts of climate change on future food security under different trade regimes are summarized in Fig. 4. These ranges represent the percent deviations in global malnutrition count in the presence of climate change relative to the 2050 baseline wherein climate change impacts are ignored. The upper and lower bounds in Fig. 4 highlight the outcomes in the absence and presence of CO₂ fertilization effects, respectively. Absent CO₂ fertilization, adverse temperature and precipitation from climate change dampens agricultural productivity. To meet

increased food demand in the future, farmers offset these unfavorable productivity shocks by using more inputs. However, such a response will drive up production costs leading to higher food prices and increased food insecurity. When CO₂ fertilization effects are considered, climate change can give rise to improved crop yields, relative to baseline, resulting in greater crop output and lower food prices in some regions. Across crop models, greater uncertainty in global food security is observed under the LPJmL crop model (Fig. 4, bottom panels). Indeed, across all GCMs the upper bounds of the deviations in global malnutrition headcount are generally higher under the LPJmL model than with the pDSSAT model (Fig. 4, top panels). Of course, this is expected as the projected reductions in crop yields are generally greater with the LPJmL crop model—especially when CO₂ fertilization effects are omitted.

Market barriers have significant implications for future food security in the presence of climate change impacts, as the range of malnutrition outcomes are substantially smaller when markets are tightly integrated (Fig. 4, right panels). In particular, the size of the adverse impacts (red upper bounds in Fig. 4) is diminished under integrated markets especially under the LPJmL crop model and HADGEM global circulation model where the rise in global malnutrition count due to climate change — when CO₂ fertilization effects are omitted — is dampened from

Fig. 4 Global food security impacts of climate change under different trade regimes for each crop model and GCM model combination. *Green lower and red upper bounds* (with and without CO₂ fertilization effects, respectively) represent deviations in global malnutrition count relative to the 2050 baseline without climate change

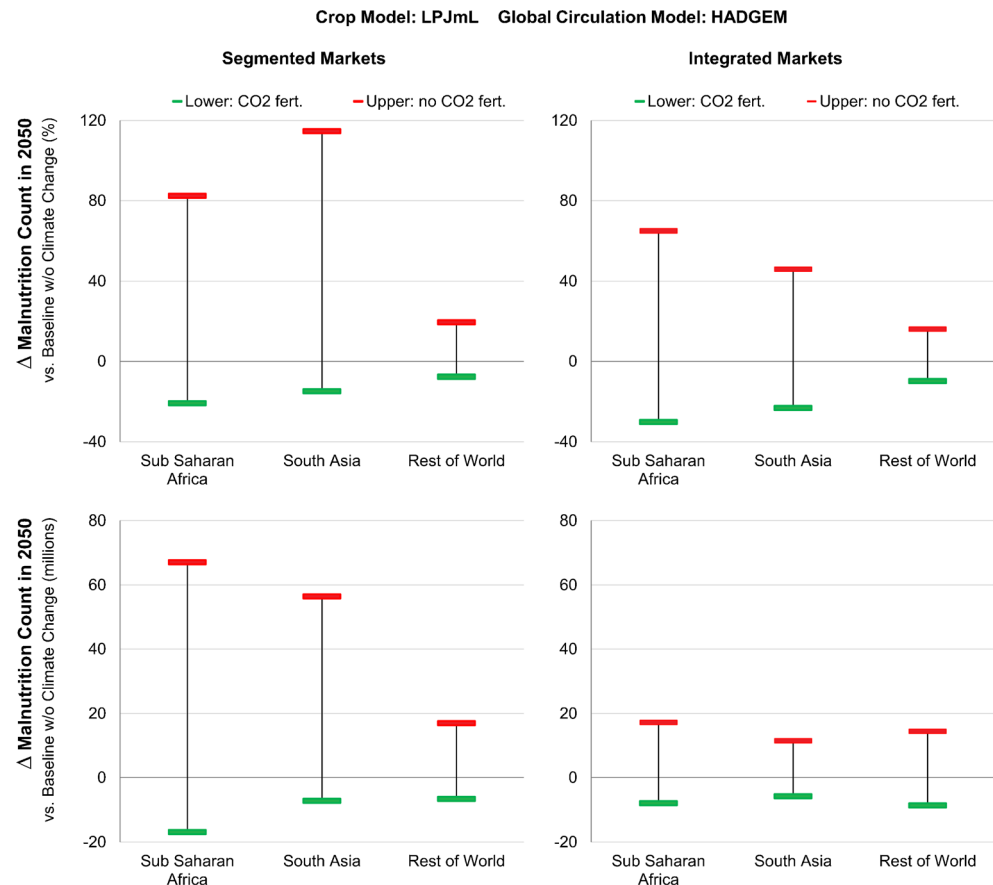


a rise in 54.8 % to an increase of 30.6 %, relative to the 2050 baseline. Note that productivity impacts from climate change alter the comparative advantage of crop production worldwide. When markets are perfectly integrated, farmers in regions which are least affected by adverse climate change shocks (or face favorable productivity impacts) are encouraged to respond to these changes by expanding crop production and increasing input use. Of course, output only expands up to the point where excess profits are exhausted, and this is facilitated by the fact that greater factor demand pushes up input prices and hence the overall cost of crop production in the climate-favored regions. Likewise, under integrated world markets, consumers can more readily adapt by purchasing crops in regions wherein market prices are relatively lower. If adverse yield impacts in one region can be offset by yield improvements in the rest of the world then it is possible that food prices will be little affected by climate change. In the presence of fully integrated world markets, it is the net global effect of climate change which is critical for long-run food production and food security. Introduction of trade barriers (market segmentation) hinders access to the world markets; thus the regional impacts of climate change play a relatively more important role in shaping regional food security.

We now shift our attention to Sub Saharan Africa and South Asia as, by 2050, most of the world's undernourished will reside in these regions. By mid-century, the number of persons exposed to extreme hunger in these regions declines significantly under our baseline scenario, highlighting the importance of other factors — particularly income growth and technological progress in agriculture—in determining future food security (Baldos and Hertel 2014). Given the future baseline, around 49 M and 81 M persons are undernourished in South Asia and Sub Saharan Africa, respectively (from 302 M and 158 M in 2006, respectively) assuming that market barriers remain. The number of malnourished persons in Sub Saharan Africa far exceed those in South Asia due to the fact that expected population growth in Sub Saharan Africa is roughly twice as large as the growth in South Asia (2.1 % vs 1.1 % per annum, respectively). If markets are completely integrated then the malnutrition count in these regions declines further (to 25 M and 27 M persons, respectively).

Figure 5 highlights the changes in regional food security in the advent of climate change. Specifically, the figure summarizes the percent and absolute changes in regional malnutrition count (top and bottom panels, respectively). Given these ranges, it appears that Sub Saharan Africa and South Asia are quite vulnerable to climate change — particularly under

Fig. 5 Regional food security impacts of climate change under different trade regimes given LPJmL crop model and HADGEM GCM model. *Green lower and red upper bounds* (with and without CO₂ fertilization effects, respectively) represent deviations in regional malnutrition count relative to the 2050 baseline without climate change



the productivity shocks predicted by the LPJmL crop model and HADGEM general circulation model. The range of malnutrition headcount — in percentage changes relative to 2050 — for South Asia is greater than the range for Sub Saharan Africa when trade distortions persist (upper left panel, Fig. 5). This is expected since the adverse climate change yield impacts are higher in the former region (−1.1 % per annum) than in the latter region (−0.3 % per annum). Of course, this range is significantly reduced when markets are fully integrated (upper right panel, Fig. 5) which suggests that future gains in food security in South Asia is relatively more sensitive to trade liberalization than in Sub Saharan Africa given the climate change impacts under the LPJmL crop and HADGEM global circulation models. In terms of absolute changes relative to the 2050 baseline (i.e., millions of malnourished people), the range of outcomes in Sub Saharan Africa exceed those in South Asia since the number of malnourished persons by 2050 is greater in the former region than in the latter region. Due to the negative impacts of climate change in these regions, removal of trade barriers can offer significant reduction in the number of malnourished persons in these parts of the world (lower panels, Fig. 5). The range of change, relative to baseline, in the malnutrition count is narrowed down from −17 M to 67 M persons to around −8 M to 17 M persons for Sub Saharan Africa while for South Asia the range is reduced from −7 M to 56 M persons to roughly −6 M to 12 M persons.⁵ When markets are fully integrated, the adverse regional impacts of climate change are mitigated as consumers can more readily adapt to changing market conditions by tapping the world markets. These findings are robust across crop model and GCM model combination (Figs. 6, 7 and 8 in the Appendix). Although climate change is critical for regional food security, it is important to bear in mind that the contribution of climate change on global future food security is relatively small when compared to other drivers of the global farm and food system (Baldos and Hertel 2014; Schmidhuber and Tubiello 2007) (see Fig. 9 in the Appendix). Overall, our findings highlight the importance of international trade in mitigating the adverse impacts of climate change on future global and regional food security — a point highlighted in previous studies as well (Reilly et al. 1994; Tobey et al. 1992).

Of course our focus here on food prices and consumption is only part of the story, climate change can have significant distributional impacts through its effect on household earnings—particularly those active in the agricultural sector. In their general equilibrium analysis of long run climate trends,

Hertel et al. (2010) conclude that the poverty impacts of adverse climate change are most severe amongst non-agricultural households in Africa and South Asia. In contrast, they found the poverty rates fall amongst agricultural households in those regions which are most lightly affected by climate change (e.g., parts of Latin America) where the effect of rising commodity prices are, on net, beneficial.

Summary and conclusions

The changing climate will reshape the global farm and food system, leading to increased frequency and intensity of extreme weather events, which, in turn, are expected to lead to greater inter-annual volatility in food supply. Furthermore, the expected food price impacts of these extreme events are likely to hit hardest those who are already vulnerable to poverty and hunger. In the longer-run, shifts in temperature and precipitation trends will alter the comparative advantage of food production across the world and could potentially dampen agricultural productivity growth in regions which have high prevalence of hunger. In order to strengthen future food security, adaptation to both inter-annual and inter-decadal impacts of climate change is needed. International trade offers an important opportunity to manage both these risks.

Based on our review of the literature, we expect that improved integration across markets and removal of trade distortions can contribute to the mitigation of food price volatility from climate extremes. However, it is important to recognize that there are significant political challenges in formulating and adopting trade agreements which will reduce existing barriers to trade in international food markets. Focusing on the long-run, we utilize a newly available library of crop yield projections under climate change to examine a wide range of climate impacts using an economic model of global agriculture. Depending on the crop model, GCM model and assumptions on CO₂ fertilization, we see that climate change contributes to considerable uncertainty in the number of malnourished persons worldwide by mid-century. We found that the populations in Sub Saharan Africa and South Asia are relatively more vulnerable to the long-term food security impacts from climate change. However, we also clearly see significant moderation in the range of malnutrition count when markets are fully integrated, highlighting the importance of international trade in mitigating the long-term food security impacts of climate change.

Acknowledgments The authors acknowledge support for the underlying research into the climate-food-energy-land-water nexus from U.S. Department of Energy, Office of Science, Office of Biological and Environmental Research, Integrated Assessment Research Program, Grant No. DE-SC005171.

This paper was part of a workshop sponsored by the OECD Co-operative Research Programme on Biological Resource Management for Sustainable Agricultural Systems.

⁵ In Baldos and Hertel (2014) wherein market barriers are ignored, the baseline malnutrition counts by 2050 in Sub Saharan Africa and in South Asia are around 47 M to 26 M persons, respectively. The ranges of malnutrition counts relative to the future baseline given climate change are around −16 M to 13 M persons for Sub Saharan Africa and −7 M to 5 M for South Asia.

Appendix

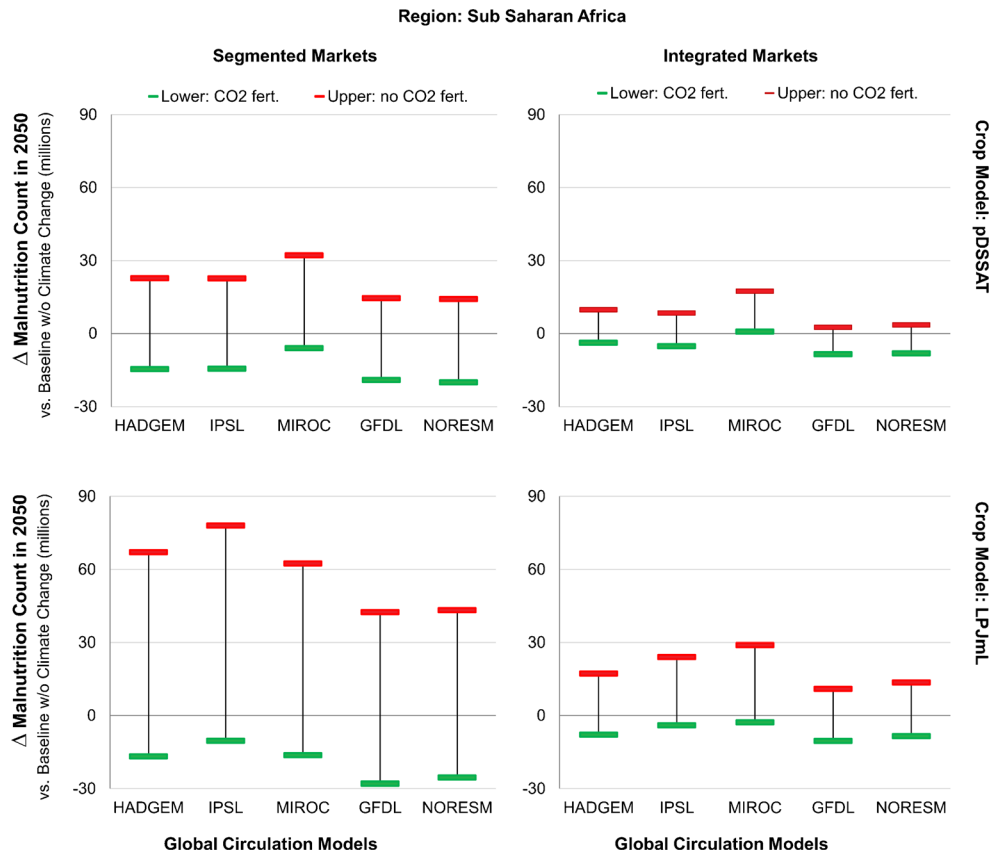


Fig. 6 Food security impacts of climate change in Sub Saharan Africa under different trade regimes for each crop model and GCM model combination. *Green lower and red upper bounds* (with and without

CO₂ fertilization effects, respectively) represent deviations in regional malnutrition count relative to the 2050 baseline without climate change

Fig. 7 Food security impacts of climate change in South Asia under different trade regimes for each crop model and GCM model combination. *Green lower* and *red upper bounds* (with and without CO₂ fertilization effects, respectively) represent deviations in regional malnutrition count relative to the 2050 baseline without climate change

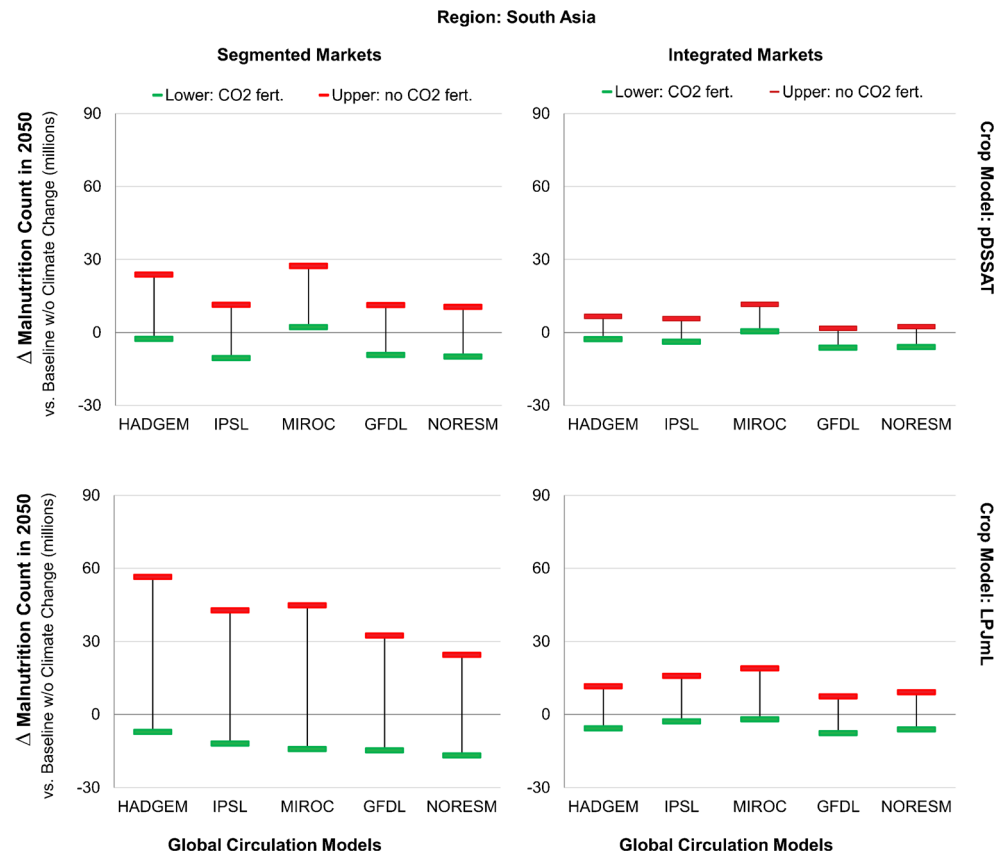


Fig. 8 Food security impacts of climate change in the Rest of the World under different trade regimes for each crop model and GCM model combination. *Green lower* and *red upper bounds* (with and without CO₂ fertilization effects, respectively) represent deviations in regional malnutrition count relative to the 2050 baseline without climate change

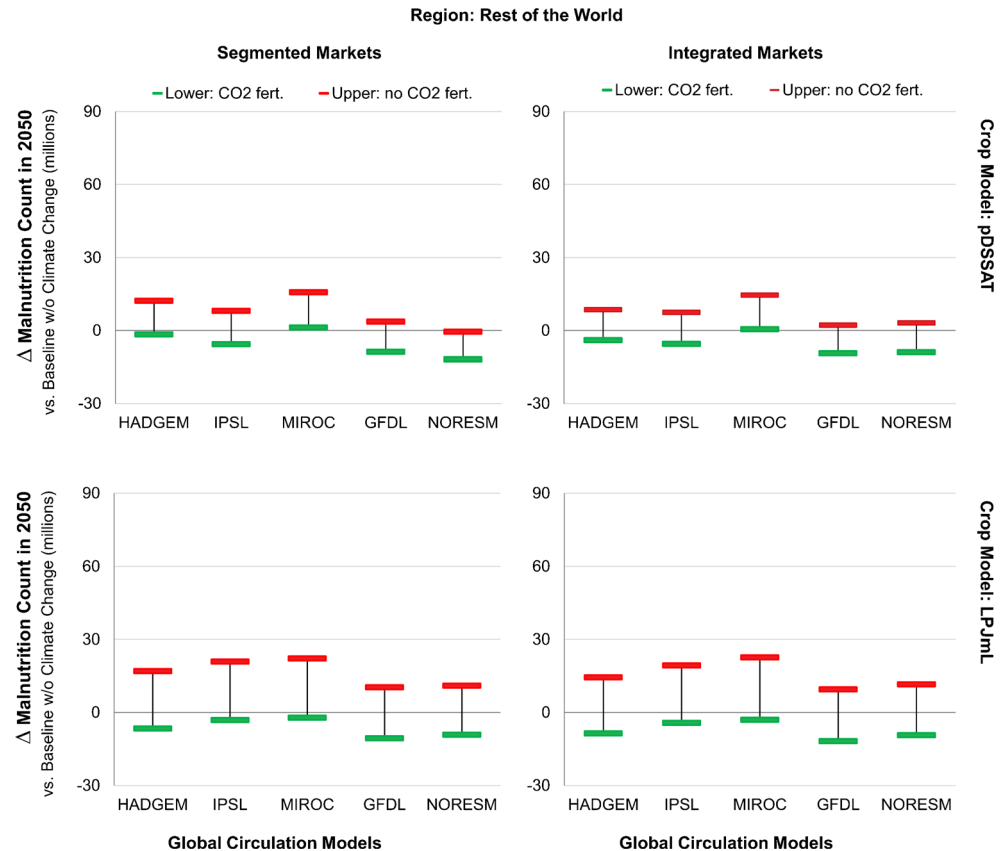
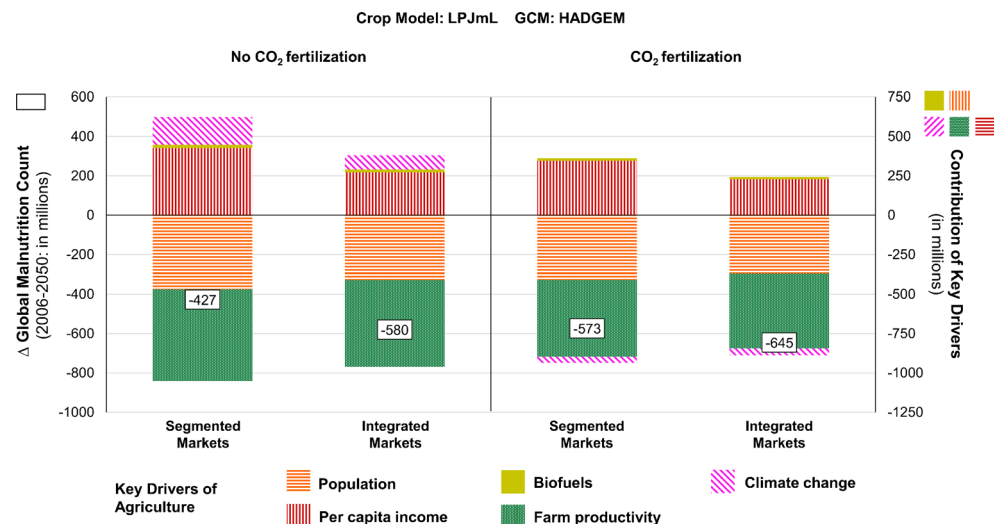


Fig. 9 Contributions of key drivers of agriculture to changes in global malnutrition count under the LPJmL crop model and HADGEM GCM model for different trade regimes. *White bars* shows the change in the number of malnourished persons from 2006 to 2050 while the *colored bars* highlight the contribution of the key drivers of agriculture to the changes in global malnutrition count



References

- Abbott, P., Hurt, C., & Tyner, W. E. (2011). *What's driving food prices in 2011?* Oak Brook: Farm Foundation.
- Ahmed, S. A., Diffenbaugh, N. S., & Hertel, T. W. (2009). Climate volatility deepens poverty vulnerability in developing countries. *Environmental Research Letters*, 4(3), 034004. doi:10.1088/1748-9326/4/3/034004.
- Ahmed, S. A., Diffenbaugh, N. S., Hertel, T. W., Lobell, D. B., Ramankutty, N., Rios, A. R., & Rowhani, P. (2011). Climate volatility and poverty vulnerability in Tanzania. *Global Environmental Change*, 21(1), 46–55. doi:10.1016/j.gloenvcha.2010.10.003.
- Anania, G. (2013). *Agricultural export restrictions and the WTO: What options do policy-makers have for promoting food security?* (Issue Paper No. 50) (p. 47). Geneva, Switzerland: ICTSD Programme on Agricultural Trade and Sustainable Development.
- Anderson, K., & Nelgen, S. (2012). Agricultural trade distortions during the global financial crisis. *Oxford Review of Economic Policy*, 28(2), 235–260. doi:10.1093/oxrep/grs001.
- Anderson, K., Rausser, G. C., & Swinnen, J. F. M. (2013). Political economy of public policies: insights from distortions to agricultural and food markets. *Journal of Economic Literature*, 51(2), 423–477.
- Baldos, U. L. C., & Hertel, T. W. (2013). Looking back to move forward on model validation: insights from a global model of agricultural land use. *Environmental Research Letters*, 8(3), 034024. doi:10.1088/1748-9326/8/3/034024.
- Baldos, U. L. C., & Hertel, T. W. (2014). Global food security in 2050: the role of agricultural productivity and climate change. *Australian Journal of Agricultural and Resource Economics*. doi:10.1111/1467-8489.12048.
- Banerjee, L. (2007). Effect of flood on agricultural wages in Bangladesh: an empirical analysis. *World Development*, 35(11), 1989–2009. doi:10.1016/j.worlddev.2006.11.010.
- Burgess, R., & Donaldson, D. (2010). Can openness mitigate the effects of weather shocks? Evidence from India's famine era. *American Economic Review*, 100(2), 449–453. doi:10.1257/aer.100.2.449.
- Diffenbaugh, N. S., Pal, J. S., Trapp, R. J., & Giorgi, F. (2005). Fine-scale processes regulate the response of extreme events to global climate change. *Proceedings of the National Academy of Sciences*, 102(44), 15774.
- Diffenbaugh, N. S., Pal, J. S., Giorgi, F., & Gao, X. (2007). Heat stress intensification in the Mediterranean climate change hotspot. *Geophysical Research Letters*, 34(11), L11706.
- Diffenbaugh, N. S., Hertel, T. W., Scherer, M., & Verma, M. (2012). Response of corn markets to climate volatility under alternative energy futures. *Nature Climate Change*. doi:10.1038/nclimate1491.
- Disdier, A.-C., & Head, K. (2008). The puzzling persistence of the distance effect on bilateral trade. *The Review of Economics and Statistics*, 90(1), 37–48. doi:10.1162/rest.90.1.37.
- Easterling, D. R., Meehl, G. A., Parmesan, C., Changnon, S. A., Karl, T. R., & Mearns, L. O. (2000). Climate extremes: observations, modeling, and impacts. *Science*, 289(5487), 2068–2074. doi:10.1126/science.289.5487.2068.
- Elliott, J., Deryng, D., Müller, C., Frieler, K., Konzmann, M., Gerten, D., et al. (2014). Constraints and potentials of future irrigation water availability on agricultural production under climate change. *Proceedings of the National Academy of Sciences*, 111(9), 3239–3244. doi:10.1073/pnas.1222474110.
- FAO. (2012). FAO food security statistics. <http://www.fao.org/economic/ess/en/>. Accessed 12 June 2012.
- FAO. (2014). FAOSTAT. <http://faostat.fao.org/>. Accessed 25 Sept 2014.
- Foster, J., Greer, J., & Thorbecke, E. (1984). A class of decomposable poverty measures. *Econometrica*, 52(3), 761–766. doi:10.2307/1913475.
- Fuglie, K. O. (2012). Productivity growth and technology capital in the global agricultural economy. In K. O. Fuglie, S. L. Wang, & V. E. Ball (Eds.), *Productivity growth in agriculture: an international perspective* (pp. 335–368). Cambridge: CAB International.

- Griffith, R., Redding, S., & Reenen, J. V. (2004). Mapping the two faces of R&D: productivity growth in a panel of OECD industries. *The Review of Economics and Statistics*, 86(4), 883–895. doi:10.1162/0034653043125194.
- Hertel, T. W., & Lobell, D. B. (2014). Agricultural adaptation to climate change in rich and poor countries: current modeling practice and potential for empirical contributions. *Energy Economics*. doi:10.1016/j.eneco.2014.04.014.
- Hertel, T. W., Keeney, R., Ivanic, M., & Winters, L. A. (2009). Why isn't the doha development agenda more poverty friendly? *Review of Development Economics*, 13(4), 543–559. doi:10.1111/j.1467-9361.2008.00483.x.
- Hertel, T. W., Burke, M. B., & Lobell, D. B. (2010). The poverty implications of climate-induced crop yield changes by 2030. *Global Environmental Change*, 20(4), 577–585. doi:10.1016/j.gloenvcha.2010.07.001.
- Hertel, T. W., Ramankutty, N., & Baldos, U. L. C. (2014). Global market integration increases likelihood that a future African Green Revolution could increase crop land use and CO2 emissions. *Proceedings of the National Academy of Sciences*, 111(38), 13799–13804. doi:10.1073/pnas.1403543111.
- IEA. (2008). *World energy outlook*. OECD Publishing. <http://www.oecd-ilibrary.org/content/book/weo-2008-en>.
- IEA. (2012). *World energy outlook*. OECD Publishing. <http://www.oecd-ilibrary.org/content/book/weo-2012-en>.
- IPCC. (2013). Climate change 2013: the physical science basis. In *Contribution of working group I to the fifth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.
- IPCC. (2014). Climate change 2014: impacts, adaptation, and vulnerability. In *Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change*. Cambridge: Cambridge University Press.
- Ivanic, M., & Martin, W. (2008). Implications of higher global food prices for poverty in low-income countries. *SSRN eLibrary*. http://papers.ssrn.com/sol3/papers.cfm?abstract_id=1149097. Accessed 19 May 2010.
- Kriegler, E., O'Neill, B. C., Hallegatte, S., Kram, T., Lempert, R. J., Moss, R. H., & Wilbanks, T. (2012). The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. *Global Environmental Change*, 22(4), 807–822. doi:10.1016/j.gloenvcha.2012.05.005.
- Limão, N., & Venables, A. J. (2001). Infrastructure, geographical disadvantage, transport costs, and trade. *World Bank Economic Review*, 15(3), 451–479. doi:10.1093/wber/15.3.451.
- Lobell, D. B., Baldos, U. L. C., & Hertel, T. W. (2013). Climate adaptation as mitigation: the case of agricultural investments. *Environmental Research Letters*, 8, 015012. doi:10.1088/1748-9326/8/1/015012.
- Lobell, D. B., Roberts, M. J., Schlenker, W., Braun, N., Little, B. B., Rejesus, R. M., & Hammer, G. L. (2014). Greater sensitivity to drought accompanies maize yield increase in the U.S. Midwest. *Science*, 344(6183), 516–519. doi:10.1126/science.1251423.
- Long, S. P., Ainsworth, E. A., Leakey, A. D. B., Nosberger, J., & Ort, D. R. (2006). Food for thought: lower-than-expected crop yield stimulation with rising CO2 concentrations. *Science*, 312(5782), 1918–1921. doi:10.1126/science.1114722.
- Ludena, C. E., Hertel, T. W., Preckel, P. V., Foster, K., & Nin, A. (2007). Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. *Agricultural Economics*, 37(1), 1–17. doi:10.1111/j.1574-0862.2007.00218.x.
- Martin, W., & Anderson, K. (2012). Export Restrictions and Price Insulation During Commodity Price Booms. *American Journal of Agricultural Economics*, 94(2), 422–427. doi:10.1093/ajae/aar105.
- Monfreda, C., Ramankutty, N., & Foley, J. A. (2008). Farming the planet: 2. Geographic distribution of crop areas, yields, physiological types, and net primary production in the year 2000. *Global Biogeochemical Cycles*, 22, 19 PP. doi:10.1029/2007GB002947.
- Müller, C., & Robertson, R. D. (2014). Projecting future crop productivity for global economic modeling. *Agricultural Economics*, 45(1), 37–50. doi:10.1111/agec.12088.
- Müller, C., Bondeau, A., Popp, A., Waha, K., & Fader, M. (2010). *Climate change impacts on agricultural yields: Background note to the World Development Report 2010 (Background Note)*. Germany: Potsdam Institute for Climate Impact Research.
- Neiken, L. (2003). *FAO methodology for estimating the prevalence of undernourishment* (Proceedings: Measurement and Assessment of Food Deprivation and Undernutrition). Rome, Italy: FAO.
- Nelson, G. C., Valin, H., Sands, R. D., Havlik, P., Ahammad, H., Deryng, D., et al. (2014). Climate change effects on agriculture: economic responses to biophysical shocks. *Proceedings of the National Academy of Sciences*, 111(9), 3274–3279. doi:10.1073/pnas.1222465110.
- O'Neill, B., Kriegler, E., Riahi, K., Ebi, K., Hallegatte, S., Carter, T., et al. (2014). A new scenario framework for climate change research: the concept of shared socioeconomic pathways. *Climatic Change*, 122(3), 387–400. doi:10.1007/s10584-013-0905-2.
- Olmstead, A. L., & Rhode, P. W. (2011). Adapting North American wheat production to climatic challenges, 1839–2009. *Proceedings of the National Academy of Sciences*, 108(2), 480–485. doi:10.1073/pnas.1008279108.
- Reilly, J., Hohmann, N., & Kane, S. (1994). Climate change and agricultural trade: who benefits, who loses? *Global Environmental Change*, 4(1), 24–36. doi:10.1016/0959-3780(94)90019-1.
- Reilly, J. M., Hrubovcak, J., Graham, J., Abler, D. G., Darwin, R., Hollinger, S. E., et al. (2002). *Changing climate and changing agriculture*. New York: Cambridge University Press.
- Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., et al. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences*, 111(9), 3268–3273. doi:10.1073/pnas.1222463110.
- Schlenker, W., & Lobell, D. B. (2010). Robust negative impacts of climate change on African agriculture. *Environmental Research Letters*, 5(1), 014010. doi:10.1088/1748-9326/5/1/014010.
- Schlenker, W., & Roberts, M. J. (2009). Nonlinear temperature effects indicate severe damages to U.S. crop yields under climate change. *Proceedings of the National Academy of Sciences*, 106(37), 15594–15598. doi:10.1073/pnas.0906865106.
- Schmidhuber, J., & Tubiello, F. N. (2007). Global food security under climate change. *Proceedings of the National Academy of Sciences*, 104(50), 19703–19708. doi:10.1073/pnas.0701976104.
- SSP Database (v 0.93). (2013). <https://secure.iiasa.ac.at/web-apps/ene/SspDb>. Accessed 1 Oct 2014.
- Tobey, J., Reilly, J., & Kane, S. (1992). Economic implications of global climate change for world agriculture. *Journal of Agricultural and Resource Economics*, 17(1), 195–204. Accessed 5 December 2014.
- Verma, M., Hertel, T., & Diffenbaugh, N. S. (2014). Market-oriented ethanol and corn-trade policies can reduce climate-induced US corn price volatility. *Environmental Research Letters*, 9(6), 064028.
- Villoria, N., Elliott, J., Choi, H., & Zhao, L. (2014). *The AgMIP Tool: a GEOSHARE tool for aggregating outputs from the AgMIPs global*

gridded crop model intercomparison project. Purdue University. <https://geoshareproject.org/tools/cropdatatool/>.

WTO General Council. (2014). Decision on public stockholding for food security purposes.



Uris Lantz C. Baldos is a post-doctoral researcher in the Center for Global Trade Analysis at Purdue University. He is the co-developer of SIMPLE: a Simplified International Model of agricultural Prices, Land use and the Environment. His current research interests focus on the global farm-food-environment nexus and on economic modelling. Uris holds graduate degrees in Agricultural Economics from Purdue University (PhD, 2014; MS, 2009).



Thomas W. Hertel is Distinguished Professor of Agricultural Economics at Purdue University, where his research focuses on the global impacts of trade, climate and environmental policies. In 2013 he was awarded the inaugural Purdue University Research and Scholarship Distinction Award.

Dr. Hertel is a Fellow, and Past-President, of the Agricultural and Applied Economics Association (AAEA). He is also the founder and Executive Director of the Global Trade Analysis Project (GTAP) which now encompasses more than 10,000 researchers in 150 countries around the world (<https://www.gtap.org>). This Project maintains a global economic data base and an applied general equilibrium modeling framework which are documented in the book: *Global Trade Analysis: Modeling and Applications*, edited by Dr. Hertel, and published by Cambridge University Press in 1997.