Global Environmental Change 41 (2016) 195–205

Contents lists available at ScienceDirect

Global Environmental Change

journal homepage: www.elsevier.com/locate/gloenvcha

Research paper

Attaining food and environmental security in an era of globalization

Thomas W. Hertel[a,b,*], Uris Lantz C. Baldos[a]

[a] Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN 47907, USA
[b] Purdue Climate Change Research Center, 203 S. Martin Jischke Drive West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 26 June 2016
Received in revised form 3 October 2016
Accepted 26 October 2016
Available online 6 November 2016

Keywords:
Globalization
International trade
Food security
Sustainability
Productivity growth
Terrestrial carbon emissions
Postharvest losses
Climate policy

ABSTRACT

Attaining the twin goals of food and environmental security in the coming decades poses a significant sustainability challenge. This paper examines the food and environmental security implications of a range of policies affecting the global food economy and terrestrial ecosystems, first in the context of historically segmented markets, and secondly in a hypothetical future world of fully integrated crop commodity markets. We begin by revisiting history, considering how food production and global land use would have evolved over the period: 1961–2006 in the presence of greater market integration. We find that there would have been greater disparities in regional crop output growth, with regions experiencing higher productivity growth tending to expand more rapidly under this counterfactual experiment. Going forward, greater market integration can be expected to reshape the way we think about future food and environmental security. In the presence of continued market segmentation, strong population growth, accompanied by robust overall income projections, results in exceptionally high demand growth, rising prices and increased non-farm undernutrition in Sub-Saharan Africa (SSA) by 2050. On the other hand, if markets are fully integrated, relative rates of productivity growth become key to the regional composition of world crop output and agricultural production and cropland grow much more slowly in SSA. We explore the implications of four policy initiatives aimed at improving food security and environmental outcomes, including enhanced on-farm productivity and reductions in post-harvest losses in SSA, reductions in food waste in the wealthy economies, and a global terrestrial carbon policy. We also evaluate the potential impacts of climate change under these two trade regimes. Our results suggest that, in some cases, the food and terrestrial implications will be radically different in a more integrated global economy.

1. Introduction

Attaining both food and environmental security in the coming decades poses a significant challenge (Davis et al., 2016; Suweis et al., 2015). On the one hand, providing affordable food and energy to consumers suggests a strategy of cropland expansion, as the world seeks to feed more than 9 billion people in 2050. Indeed some of the Integrated Assessment Models project sizable cropland expansion over the coming decades (Schmitz et al., 2014) – particularly under scenarios incorporating bioenergy into climate mitigation policy (Rose et al., 2012; Wise et al., 2009). On the other hand, preservation of biodiversity and forest carbon stocks mitigates against such expansion. Improving agricultural productivity on existing croplands is therefore often advocated as an important option for meeting food security objectives in an environmentally sustainable way (Burney et al., 2010).

However, in the presence of smoothly functioning international trade, isolated improvements in productivity can result in rapid expansion of cropland, with attendant degradation of natural resources (Angelsen and Kaimowitz, 2001; Lambin and Meyfroidt, 2011). These potential environmental risks notwithstanding, international economic integration has been shown to offer significant food security benefits in the context of extreme weather events (Burgess and Donaldson, 2010; Verma et al., 2012), provided governments avoid the imposition of export restrictions (Puma et al., 2015). Economic integration can also enhance food security in the context of long run changes in agricultural productivity due to climate change (Reilly et al., 1994; Baldos and Hertel, 2015). So is globalization good or bad for food security and the terrestrial ecosystem? More to the point, given that greater economic integration is viewed by many as inevitable, how are such market developments likely to alter our view of the

---

* Corresponding author at: Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN 47907, USA.
E-mail address: hertel@purdue.edu (T.W. Hertel).

http://dx.doi.org/10.1016/j.gloenvcha.2016.10.006
0959-3780/

challenges facing the global food system? We explore these questions in the context of historical events as well as prospective policy interventions in the food and terrestrial ecosystems, including improvements in agricultural technology, reductions in post-harvest losses and food waste, as well as climate change mitigation policies.

The history of agricultural markets has been one of episodes of globalization, followed by periods of protectionism and isolation (Johnson, 1973). During times of war there is great interest in ensuring food self-sufficiency, thereby leading to restrictions on imports to stimulate domestic production. Yet another important driver of agricultural protection is the political-economic power of agricultural interest groups. As Hayami and Ruttan (1985) and Anderson et al. (2013) demonstrate, as countries move from subsistence farming and low income levels, to commercial agriculture and higher per capita incomes, government policies directed at the farm sector shift from net taxation to net support of agriculture. The logic is that, at low levels of economic development, the farm sector comprises millions of relatively poor, rural producers, with little political influence. It is hard for them to organize, and, even if they were able to do so, their share of overall employment and GDP is so large as to preclude the feasibility of significant income support for such a large segment of the population. Indeed, with underdeveloped institutions and small manufacturing sectors, agricultural commodities are one of the few tangible items which can be effectively taxed in the world's poorest countries.

Over time, as countries become wealthier, and their manufacturing and service sectors grow, wages rise, farms consolidate, agriculture becomes more capital intensive and the number of farmers inevitably declines. This improves the opportunities for political mobilization. Also, with farming accounting for a smaller share of GDP and economy-wide employment, richer countries, with well-developed industrial and service sectors, and strong government institutions, can now draw on a broad-based tax system to subsidize the shrinking farm sector as has been the case most recently in China (Gale, 2013). So it is hardly surprising that the rich countries of the world tend to subsidize agriculture (Anderson, 2009).

From the point of view of world markets, a critical question is how this support is provided to the farm sector. Up until the Uruguay Round Agreement of the World Trade Organization (WTO) it was very common to intervene at the border with quotas and export subsidies, preventing smooth adjustments in trade in response to changing supply and demand conditions (Martin and Winters, 1997). This wreaked havoc in world markets, and contributed to substantial differences between domestic and world prices. Subsequently, there were important efforts to decouple producer support from production and consumption decisions – particularly in the European Union (Swinnen, 2010). This has improved the functioning of global markets, although many barriers to agricultural trade remain (Anderson, 2009) and these have proven to be stumbling blocks on the path to a new WTO agreement. The current Doha Development Round of WTO talks was initiated in 2001, yet still has not been successfully concluded.

Frustration with the lack of progress in multilateral trade negotiations gave rise to an explosion of bilateral and regional trade agreements. Indeed, since the year 2000, more than 200 bilateral trade agreements have been reported to the WTO (WTO Regional Trade Agreements, 2016). One of the most important developments over the past few decades has been the enlargement of the EU to 28 countries, along with associated reforms to the EU's Common Agricultural Policy (CAP). This resulted in the elimination of its export subsidies and the conversion of much of the producer support into "decoupled" payments which less trade-distorting (European Commission, 2012). The EU has also established free trade agreements with many of its trading partners, as have the US, Japan and many other large economies. Nonetheless, more than half of the tariff cuts between 2001 and 2013 were the result of unilateral trade reforms as countries have sought to become part of the 'global value chains' now coming to dominate the modern food economy (Bureau et al., 2016). In order to effectively participate in such value chains, economies must reduce the cost of goods passing across national borders. Development of these value chains has been further facilitated by major investments in physical and logistical infrastructure, including increasing use of electronic customs clearance (Arvis et al., 2012).

Globalization not only influences commodity markets, it also affects the flow of knowledge, capital and labor between countries and between the farm and non-farm sectors. In the wake of the post-2007 commodity price boom, there was a sharp increase in interest by foreign investors in farmland – particularly in Africa (Deininger and Byerlee, 2010). This was dubbed the 'land grab' by many commentators, and, although the number of investments actually consummated was far less than preliminary commitments indicated, this wave of interest demonstrated the great potential for global capital flowing into the agricultural sector. While many saw this as a threat to native communities and the environment (Margulis et al., 2013), others saw this as a chance to bring in new technologies and infrastructure, thereby modernizing the farm sector and boosting productivity in some of the least developed parts of the global food system (World Bank, 2009). Closer integration of farmers into national and international capital markets is expected to make producers more responsive to market conditions – allowing for rapid expansion in the face of high commodity prices – which, as we will see below, also has important implications for food security and environmental outcomes.

In this paper, we explore the frequently posited hypothesis that globalization is bad for food and environmental security. We do so by exploiting a historically validated, global economic modeling framework which allows for analysis of the impacts of five pressing issues in food and environmental security. These are first examined under the assumption that food markets will perform in the future as they have in the past – namely with segmentation between national and global markets. We then turn to a counterfactual representation in which full market integration is assumed. By contrasting the impacts of these five scenarios under market segmentation vs. full integration, we are able to evaluate how globalization can alter the consequences of policy interventions aimed at improving food and environmental security.

2. Materials and methods

2.1. A model for analysis of globalization

In order to understand the historical interplay between globalization, on the one hand, and food and environmental security on the other, it is necessary to utilize a global economic model of agriculture, food and the environment. Here we draw on the partial equilibrium model of agricultural trade nick-named SIMPLE (A Simplified International Model of crop Prices Land use and the Environment) (Baldos and Hertel, 2013; Hertel and Baldos, 2016). As its name suggests, this has been designed around the principle that a model should be no more complex than is absolutely necessary to understand the basic forces governing the global supply and demand for crops, cropland and food prices. The model disaggregates the world economy into fifteen regions, each producing an aggregate crop commodity using a variable combination of land and nonland inputs (Fig. A1 in Supplementary material). Substitution of non-land inputs (e.g., fertilizers, farm labor and machinery) for land in crop production offers scope for endogenous intensification of production, allowing for crop yield growth even in the absence of technological change under increasing scarcity. In addition, we allow for exogenous growth in agricultural productivity, which we expect to be driven by investments in agricultural research and development, changes in policies, and by changes in climate. The supply of land to crops is also price-sensitive. Cropland may be bid away from competing uses, with the size of this area response varying across geographic regions.

Crop production in SIMPLE has four potential uses: direct consumption, livestock feed, food processing, and biofuel feedstocks. Food demands are price- and income-sensitive, but become less as per capita incomes rise (Muhammad et al., 2011). Rising incomes also cause consumers to diversify their diets, which, at early stages of economic development, means adding relatively more livestock and processed foods. Production of both these commodities requires crop inputs – the demand for which can be altered by technological progress in those sectors (e.g., more feed efficient livestock).

In its initial implementation, SIMPLE assumed fully integrated markets, and, while the model was able to faithfully reproduce global consumption, production and land use change over the period 1961–2006, it did a poor job determining where the production and cropland conversion occurred (Baldos and Hertel, 2013). Subsequently the model was refined to incorporate market segmentation – a feature which is widely used in global trade models (e.g., Hertel, 1997). The specific form of market segmentation used is that proposed by Armington (1969) who postulated that domestic and imported products were differentiated goods, albeit potentially close substitutes. This trade specification has since garnered considerable empirical support in agricultural trade (e.g., Villoria and Hertel, 2011). The greater the differentiation between domestic and international markets, the more segmented are the crop commodity markets.

We apply the same segmented markets specification to domestic producers. Aggregation across domestic farms producing differentiated goods and having limited market access gives rise to a 'constant elasticity of transformation' between domestic and international goods (assumed to be equal in magnitude to the elasticity of product substitution). When many of a country's farmers face high transport costs and have poor access to world markets, the absolute value of this transformation elasticity is small, and domestic producers are relatively unresponsive to world price changes. On the other hand, when farmers are well-integrated into the world market, we expect a strong supply response to international prices. In the limit, if all producers have access to both markets, there is no market segmentation whatsoever, and we have *complete market integration* – with just one price for crops, worldwide. While this limiting case is unrealistic, it does approximate the situation observed in other globalized markets (e.g., wearing apparel, electronic components) and therefore offers an important counterpoint to the historical environment of segmented agricultural markets.

The extent of market segmentation is captured by the elasticities of substitution and transformation between domestic and international goods as well as the initial shares of international goods in the consumption and production bundles. The absolute value of the trade elasticities are set to 3, in keeping with the broad thrust of the empirical evidence for international substitution of crops (Hertel et al., 2007). In the Armington specification, the initial extent of market penetration (the share of spending on international goods) also plays a central role in determining the degree to which the global and regional crop markets are linked. If no international goods are available (zero share), then domestic and international consumer prices will not be linked at all. Similarly, if local producers have no presence in international markets (zero supply share to the global market), they will not respond to changing global prices. On the other hand, if these international market shares are large, then international prices will be readily transmitted into the domestic market.

Fig. 1 reports the international shares in regional consumption (red) and supply (green) for crops across the fifteen regions in SIMPLE. The differences across regions are striking. The largest foreign consumption share is for Japan and Korea, where fully half of its use of crops is satisfied by the international market. This is followed by the EU, Central America and Central Asia. These are all regions where developments in international markets are expected to be felt strongly by consumers. In contrast, consumers in Sub-Saharan Africa (SSA), South America, South Asia and China are expected to be relatively insulated from international prices in this framework. On the supply side, we see that Australia/New Zealand, EU, Southeast Asia, Canada/US and South America are heavily integrated into international markets. In North Africa, SSA, South Asia, China and Japan/Korea, producers are quite insulated from international market developments.

Once we factor in the interplay between supply and demand in the domestic market, we find that the overall degree of price transmission from global to regional markets is smallest for SSA, South Asia and China (Appendix Table A1 in Supplementary materials). In the case of SSA and South Asia, this has to do with high barriers to trade – both policy-induced (Anderson, 2009) and owing to weak trade facilitation (Arvis et al., 2012). In the case of China, the world's largest agricultural economy, part of the reason for this weak link is the immense size of the Chinese food economy. In addition, domestic agricultural policies have a strong self-sufficiency orientation (Gale, 2013).

In order to assess the food security impacts of alternative scenarios we will focus on changes in the malnutrition headcount in the lower income regions of the world. To compute this, we follow the approach outlined in Baldos and Hertel (2014). This involves converting food consumption in each region into kilocalories using conversion factors from the FAO, thereupon explicitly modeling the distribution of caloric intake across the entire population using a log-normal distribution. The parameters of these distributions are calibrated in order to reproduce FAO (2012) estimates of the mean and standard deviation of per capita daily caloric consumption, as well as the undernutrition headcount in each of the 15 model regions (see Appendix A1 in Supplementary materials). As changing prices and incomes alter per capita consumption in SIMPLE, we assume that the entire distribution shifts in concert, thereby inducing changes in the undernutrition

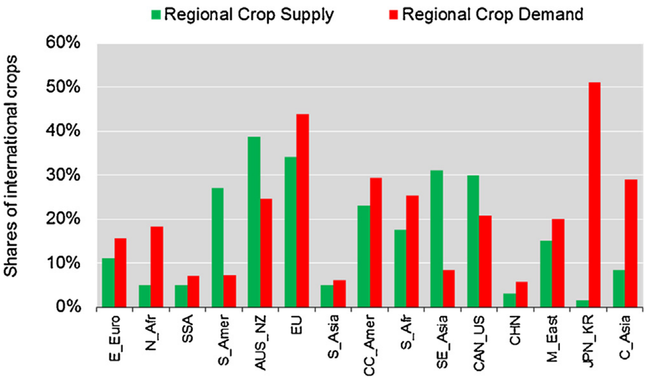

Fig. 1. Shares of international goods in the regional demand for (red) and supply of (green) crops in 2006. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

headcount (the number of persons consuming below the FAO-determined minimum caloric threshold). This approach to modeling changes in malnutrition has been validated over the decade 1991–2001, using measurements provided by the FAO (Baldos and Hertel, 2014; Fig. 1). Overall, the model does a reasonable job predicting observed changes in the incidence of malnutrition, although it over-estimates reductions in the malnutrition headcounts in South Asia and China, where rapid growth was less beneficial to the poor due to rising income disparities.

Our metric of environmental outcomes is based on cropland conversion. While this is admittedly just one of many potential metrics, it is arguably the main avenue by which agriculture influences the natural environment. Indeed, land conversion is a major source of greenhouse gas (GHG) emissions, worldwide, accounting for more than half of global emissions associated with agricultural production (Vermeulen et al., 2012). Agricultural expansion is also one of the most important sources of biodiversity loss (Phalan et al., 2011). In this version of SIMPLE, we focus on terrestrial carbon losses from cropland conversion. To estimate these, we multiply the predicted land cover change by carbon emissions per hectare estimated from West et al. (2010). Since the latter are estimated at the grid cell, they must first be aggregated to the 15 regions in SIMPLE. We do so by weighting the pixel-based measure by the actual amount of “available” land for clearing, factoring in existing cropland as well as accessibility of non-cropped land.

The SIMPLE model has previously been used in studies focusing on climate change impacts (Baldos and Hertel, 2014, 2015), climate mitigation and adaptation (Lobell et al., 2013), assessing the impact of green revolutions on land use and food security (Hertel et al., 2014), and for long run food security analysis (Hertel et al., 2016). In this paper we utilize the model to explore in depth the interplay between globalization, on the one hand, and food and environmental security outcomes, on the other – all in the context of five different scenarios currently receiving attention by policy makers.

2.2. Model validation

As noted above, SIMPLE has previously been validated by running the model over the 1961–2006 period (Baldos and Hertel, 2013), using observed regional population, income, and total factor productivity growth in agriculture as exogenous drivers and comparing endogenous outcomes to their observed counterparts (FAOSTAT, 2015; FAO Statistical Database, 2015 and World Bank GEM Database, 2015). We begin our validation exercise by revisiting this historical validation, only now with the segmented markets version of SIMPLE. As with earlier versions, the current model performs well at global scale with crop output rising a nearly the same rate as observed (191% vs. 204% observed – see WORLD total in Fig. 2), with modest increases in global land use (8.0% vs. 12% observed) due to strongly rising crop yields (169% vs. 192% observed), even as global prices fell (−42% vs. −38% observed).

Since SIMPLE under-predicts output growth at the global scale, it logically follows that this is also the case in most of the regions reported in Fig. 2. The divergence between observed and predicted output change in the Latin America & Caribbean region is the most striking. Given the simplicity of the model, it is hardly surprising that there would be large divergences at the regional level. Indeed, predicting regional changes in agricultural output and trade has long plagued modelers – even those using far more complex frameworks (McCalla and Revoredo, 2001). However, with the exception of Latin America and the Caribbean, the rank ordering of output growth rates is the same in the model as in the historical record. Based on these observations, we believe that the segmented markets version of SIMPLE offers a valid starting point for analyses of global change and the cropping sector. In the results presented below, we use SIMPLE as a laboratory for examining the consequences of globalization for food and environmental security.

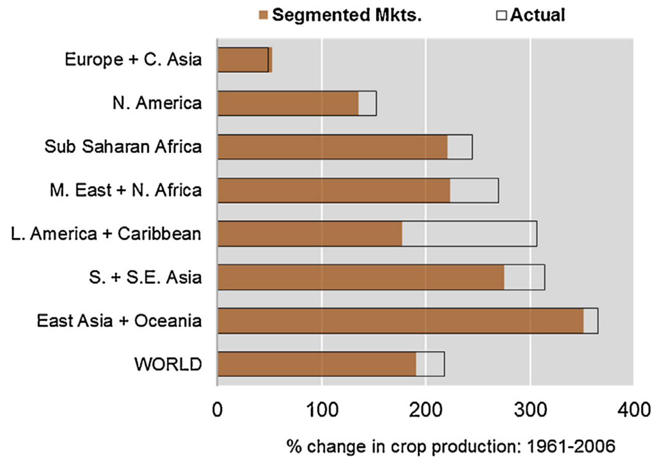

Fig. 2. Regional changes in output from 1961 to 2006 (% change): Observed vs. predicted.

Note: The following regional mapping is used to link the 7 region to the 15 region version of SIMPLE: *East Asia* + Oceania (AUS_NZ, CHN_MNG, JPN_KR); *Europe* + C. Asia (E_Euro, EU, C_Asia); *L. America + Caribbean* (S_Amer, CC_Amer); *M. East* + N. Africa (N_Afr, M_East); *N. America* (CAN_US); *S.* + S.E. Asia (S_Asia, SE_Asia); *Sub Saharan Africa* (SSA, S_Afr).

3. Results and discussion

3.1. Decomposition of drivers of change

The first set of bars in Fig. 3 reports the decomposition (colored bars) of the predicted historical crop output changes (open circles give totals) for the regional and global aggregates *under segmented markets*. Looking at the global results (Fig. 3, far right, WORLD), we see that the largest contributor to crop output growth historically was population growth, followed by agricultural productivity growth, with income growth coming in third place.

Turning to the regional results, we rank each region from smallest to largest (moving from left to right) based on the predicted historical changes in crop production. We see that Eastern Europe and Central Asia both showed slow growth in crop production during this period, while China experienced a dramatic rise in output relative to other regions. The colored segments of each bar show that in the historical world of market segmentation the underlying drivers of output change varied greatly across regions. In most regions, strong agricultural productivity growth (large green segment) coincides with greater supply expansion. But for Sub-Saharan Africa (SSA) which faced slow per capita income growth and experienced very little agricultural productivity growth, we see that nearly all of the increased output for this region is driven by population (red segment). In contrast, population growth accounts for just one-third of the historical crop output growth in China. China’s per capita income, which rose at a record-setting pace over this period, explains another third of that region’s historical output growth (orange segment). And agricultural total factor productivity (TFP) – which was also very rapid in China due to economic reforms and massive investments in agricultural technology – accounts for the remaining third. In summary, in a world of segmented markets, the drivers of change in the global crops sector vary greatly across regions.

3.2. Rewriting history with integrated markets

With these tools in hand, we can now ‘rewrite history’, in order to explore the *counterfactual* implications of globalization. More specifically, we rerun the model over this historical period allowing for fully integrated commodity markets such that there is a single crop commodity price, worldwide. In addition, we double the nonland factor supply elasticities to agriculture to reflect the impact which globalization is expected to have on agriculture’s access to national and international labor and capital markets. This has the effect of increasing agriculture’s supply response to producer price changes – the expected outcome of globalization of labor and capital markets. This section presents an analysis of these results.

Return to Fig. 3 and contrast the historically segmented market outcomes with those obtained when we rerun history under *integrated commodity and factor markets* (right-hand bars in Fig. 2). Market integration results in greater expansion in regional crop production in the OECD regions (Australia/New Zealand, EU, Canada + US, Japan + Korea) and in South America. Of course, not all regional crop sectors benefit from market integration and some even face steep declines in crop production – a point which we will revisit shortly. With integrated markets, it no longer matters where in the world economy the increased demand emerges. With just one price for the crop commodity, supply and demand are equated at global scale. This means that production in all regions is stimulated by the rising population and/or income in any region of the world, thereby resulting in changes in the contribution of income and population to regional output growth. How crop output growth varies across regions hinges critically on the relative rates of productivity, population and income growth compared to the world average.

Appendix Fig. A2 in Supplementary materials reports each region’s overall crop production as well as crop TFP, population and per capita income growth rates over this historical period, relative to their global averages. From this, we see that SSA has the slowest relative productivity and highest population growth over this period, and therefore, if historical markets had been integrated, crop output expansion in this region would have been much slower under integrated markets (compare the height of the open circles in Fig. 3). SSA consumers would have purchased more food on the world market, reducing domestic output growth from 225% to just 193% if there were no barriers to trade. In contrast, North America would have produced more far output in the fully integrated economy, leveraging their above-average TFP growth rates into a larger global market share, with output growth jumping from135% in the presence of market segmentation to 214% in the fully integrated case.

Europe, Central Asia, East Asia and Oceania offer exceptions to this pattern of crop supply expansion. For both Europe and Central Asia, TFP growth was below the world average, but crop output growth would still have been higher under integrated markets than under the historically segmented case. This reflects the fact that overall demand growth in these regions was weak, as evidenced by the slow rate of population and income growth, relative to the rest of the world (Fig. A2 in Supplementary materials, panels c and d). With weak local demands, it is not surprising that output growth was slow under segmented markets. Integrated markets allow Europe to tap into the more rapidly growing global demands, and this serves to boost output, relative to the segmented markets case. In contrast, despite stellar crop TFP growth compared to the rest of the world, regional production in East Asia and Oceania does not keep pace with rising local food demand due to very high rates of per capita income growth. This gives rise to increased net imports of crop commodities under integrated markets.

3.3. Projections for global agriculture: 2006–2050

Given the importance of the market integration assumption for the historical evolution of crop output, it is hardly a surprise that this is also critical for future projections. Of course, the problem with making such projections is that the underlying drivers of change are uncertain. This is particularly true for productivity growth, which is, notoriously difficult to measure, let alone forecast several decades into the future. In the projections presented below (see Appendix for more details), we will simply assume that the historical patterns of productivity growth persist into the future (Ludena et al., 2007; Fugli, 2012). Fig. 3 reports the projections of future crop output growth under the two alternative assumptions about markets. As before, we rank the regional outcomes from smallest to largest change based on the segmented markets result (left to right) and also report the global changes (far right results).

The first thing to note about the results in Fig. 4 is the more modest overall growth rates in crop output, as compared to the 1961–2006 period shown in Fig. 3. Globally, we project a 90% increase in crop production for the period 2006–2050 – far below the 200% observed rise during the historical period of the same length. Baldos et al. (2016) show that this slowdown is largely due

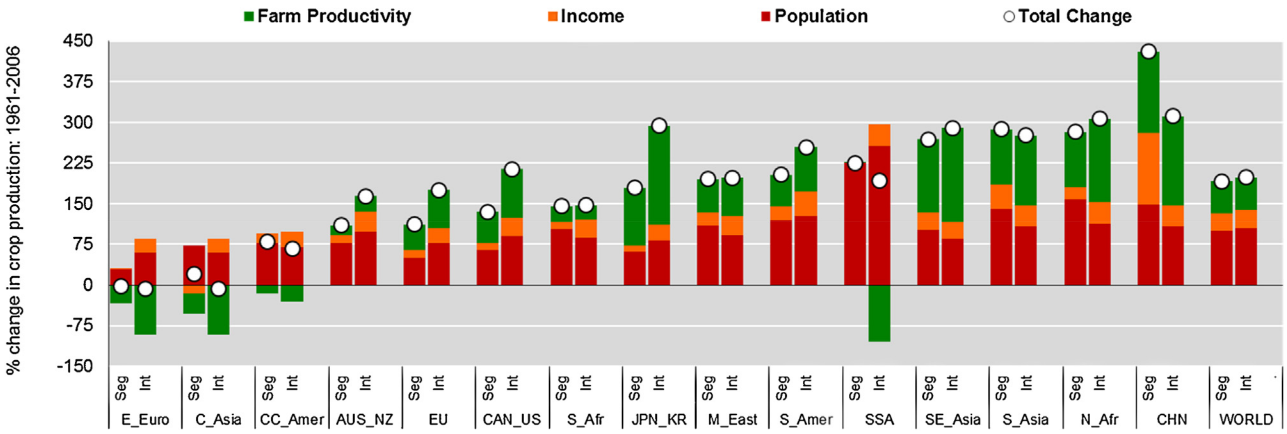

Fig. 3. Decomposition of *historical drivers* of regional output growth under segmented and integrated markets (paired colored bars, respectively). Regions are ordered from lowest (left) to highest (right) based on% change in total crop output (open circles) under segmented markets. Exogenous drivers include: red = population, orange = per capita income growth, green = productivity growth.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

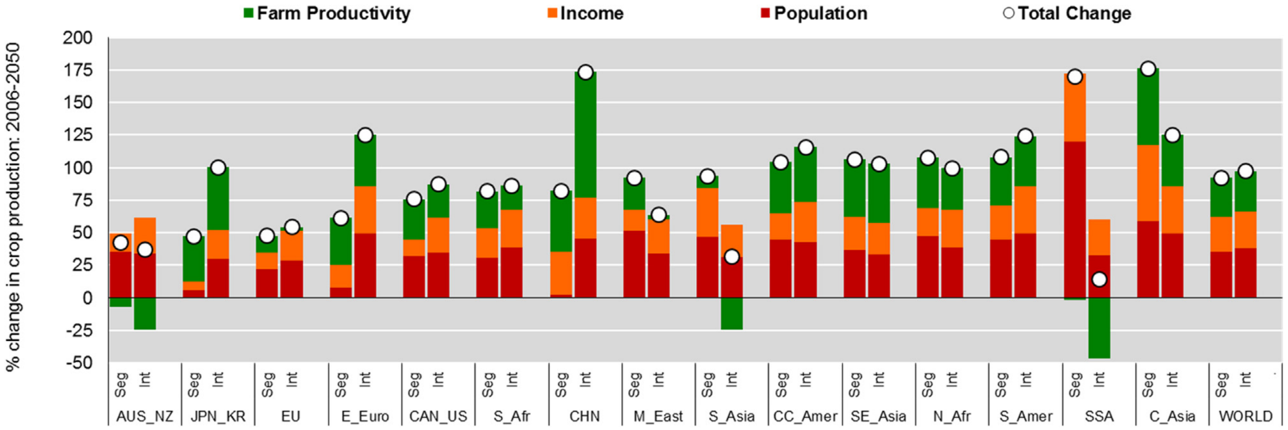

Fig. 4. Decomposition of *future drivers* of regional output growth under segmented and integrated markets (paired colored bars, respectively). Regions are ordered from lowest (left) to highest (right) based on% change in total crop output (open circles) under segmented markets. The following color scheme is used in the decomposition: red = population, orange = per capita income growth, green = productivity growth.(For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

to the slowing population growth rate under the “middle of road” scenario taken from the Shared Socioeconomic Pathways projections (SSP2) (Kriegler et al., 2012; O’Neill et al., 2014). The slowdown is particularly pronounced in the richer economies where added consumers historically generated strong demand for additional consumption. Slowing population growth, coupled with robust income projections for the world’s developing countries, explain the dramatic shift in the relative importance of income and population as drivers of future world crop output growth in Fig. 4 (rightmost bars, orange vs red segments), with income growth assuming a larger role in the future, as opposed to the past (recall Fig. 3), through its impact on diets (Alexander et al., 2015).

Under the segmented market regime, developed regions exhibit sluggish expansion in crop output, relative to developing regions, which is expected given the slow rise in domestic food demand in the rich countries – as income and population growth slowdown in the future and diets reach satiation levels. Among developing regions, crop production in South America, SSA and Central Asia are expected to increase significantly. From the decomposition of regional output drivers, it is clear that strong population and income growth in SSA creates considerable growth in the local demand for food, which is largely satisfied by domestic output growth in the case of market segmentation – rising by 170% over this period. This stands in sharp contrast to the case of integrated markets (right hand bars in Fig. 3), wherein the low rate of productivity growth in SSA leads to a significant diversion of production to other regions resulting in sluggish crop production growth (14%) and massive net imports of food crops. The same sharp reduction in domestic production is also evident in South Asia wherein slow productivity growth is expected. We observe a notable rise in crop production in the Japan/Korea, Eastern Europe and China regions which are expected to expand production more when we move from segmented to integrated markets given their relatively strong agricultural productivity growth which contrasts with a very small rise in domestic food demand.

3.4. Implications of market integration for food security and terrestrial ecosystems

Given the very different pattern of crop output growth from 2006 to 2050 under segmented and integrated markets, we expect that there will also be rather different consequences for food and environmental security due to interventions in the global food and terrestrial ecosystems. In this section we consider four types of policy interventions, in addition to one global environmental change scenario (climate change). The first two policies are primarily motivated by food security concerns: improvements in agricultural technology and reductions in post-harvest crop losses, while the second two policy scenarios are environmentally motivated and include: reductions in food waste in rich countries, as well as a REDD+ forest carbon sequestration initiative. Given its food and terrestrial vulnerabilities, we focus our regional analysis on Sub-Saharan Africa, but we also report global impacts. A complete set of regional impacts is reported in the Appendix.

3.4.1. Implications of a prospective African green revolution

In light of the slow productivity growth in Sub-Saharan Africa (SSA) over recent decades, we begin by analyzing the potential impacts of a much-hoped for African Green Revolution (GR) in which investments in new technologies, as well as adaptation of existing technologies boosts the rate of crops productivity growth. Here, we follow Hertel et al. (2014) in postulating an increase in the annual rate of growth in SSA crop productivity, beginning in 2025 and comparable in magnitude to that achieved in Asia during the historical green revolution (Stevenson et al., 2013). To simplify the experimental design, and to facilitate interpretation, we implement the African Green Revolution experiment as a supplement to the baseline simulation – implemented subsequently on the updated, 2050 data base. This means that the percentage changes reported in Table 1 refer to changes, relative to the 2050 baseline. This is done for each of the two trade regimes (each of which produces a different 2050 baseline) – first in the presence of historically segmented markets, and then under the assumption of integrated commodity and factor markets.

Globally, we observe (Table 1) a somewhat larger reduction in crop price with market segmentation, as is also the case for nonfarm undernutrition under the GR scenario. (We abstract here from on-farm nutrition which is more complex and depends on whether individual farms are net sellers or buyers of crops.) Of special note is the dramatic difference in the impact on local prices in the SSA region. With historical market segmentation, local prices do not move in strict lock-step with international prices, so an increase in local crop supplies has a depressing effect (relative to baseline) on domestic prices in the SSA region. This, in turn, has a favorable impact on nonfarm undernutrition, which falls by 46.1%, relative to baseline 2050 levels under segmented markets. This outcome contrasts sharply with the integrated markets scenario in which SSA prices fall in lockstep with international prices – which drop by just 5.5%. As a consequence, the benefits to SSA food consumers are much more modest (10.8% drop in non-farm undernutrition).

Table 1
Food and Environmental Security Impacts of Policies under Segmented vs. Integrated Markets (% change relative to 2050 baselines for segmented and integrated markets, respectively).

Policy Scenarios	Global Impacts (in%)							
	Crop Price		Nonfarm Undernutrition		Cropland		Terrestrial Carbon Emissions	
	Segmented	Integrated	Segmented	Integrated	Segmented	Integrated	Segmented	Integrated
African Green Revolution	−7.9	−5.5	−23.0	−5.9	−1.6	0.8	−1.8	3.1
SSA Postharvest Loss Reduction	−1.8	−0.9	−5.7	−1.0	−0.3	0.3	−0.3	0.9
Food Waste cuts in Rich Countries	−2.1	−1.4	−1.6	−1.5	−0.7	−0.6	−0.7	−0.7
REDD+ global climate mitigation	1.9	2.2	2.4	2.4	−11.4	−10.5	−15.1	−14.2
Climate Change impacts	27.6	24.4	45.2	27.2	4.4	3.0	5.2	5.1

Policy Scenarios	Regional Impacts: Sub Saharan Africa (in%)							
	Crop Price		Nonfarm Undernutrition		Cropland		Terrestrial Carbon	
	Segmented	Integrated	Segmented	Integrated	Segmented	Integrated	Segmented	Integrated
African Green Revolution	−34.8	−5.5	−46.1	−10.8	−1.8	25.5	−1.8	25.5
SSA Postharvest Loss Reduction	−9.0	−0.9	−11.5	−1.8	0.1	5.9	0.1	5.9
Food Waste cuts in Rich Countries	−0.9	−1.4	−2.4	−2.8	−0.6	−0.9	−0.6	−0.9
REDD+ global climate mitigation	1.7	2.2	3.3	4.5	−21.8	−21.6	−21.8	−21.6
Climate Change impacts	22.9	24.4	47.0	53.2	6.1	6.9	6.1	6.9

See Appendix Table A2 in Supplementary materials for the complete set of results for all regions. The percentage changes reported in for climate change impacts differ from those reported in Baldos and Hertel (2015), since the latter study computed these changes relative to the 2006 benchmark.

Therefore, in the context of an African GR, globalization limits the food security benefits from an African GR.

What about the environmental consequences of the African GR? Here, we focus on changes in cropland and terrestrial carbon fluxes (Table 1). Begin with the bottom panel which reports results for SSA. Here, we see that, in the case of historically segmented markets, the African GR reduces cropland area in the SSA region, while under integrated markets cropland area expands strongly. These results are explored in depth by Hertel et al. (2014), who note that, under integrated markets there is scope for local producers to expand strongly without depressing local prices very much. In effect African farmers displace production elsewhere in the world. And since SSA has a relatively low carbon efficiency in crop production (low yields relative to terrestrial carbon stocks), this causes both local and global terrestrial carbon emissions to rise (Table 1, final column). Thus, in the presence of globally integrated markets, it will be critical to protect environmentally sensitive areas in the SSA region – particularly if the programs aimed at boosting African agricultural productivity are successful.

3.4.2. Reducing postharvest losses in Africa

A global food policy issue which has received considerable attention recently relates to the food system losses that occur between the harvest and the wholesale/retail distribution system. UN-FAO estimate these losses to be as high as 28% of total production in Africa (FAO, 2011), although such macro-scale estimates are very crude and farm survey results suggest that they may significantly overstate the magnitude the problem (Kaminski and Christiaensen, 2014). Efforts are currently underway to reduce post-harvest losses through a variety of measures. One of the most successful has been the Gates Foundation initiative to introduce improved crop storage technologies (Murdock and Baoua, 2014). However, despite the introduction of low cost storage bags, adoption of that technology has been hindered by the development of a supply chain for these bags, as well as credit for their purchase. As with on-farm production technologies, it is not enough to develop the new technology, it must be disseminated and widely adopted in order to have an impact on food security. Current efforts are aimed at addressing these issues (https://www.picsnetwork.org/).

Here, we explore the impacts of reduced post-harvest losses on food prices, undernutrition and terrestrial carbon fluxes from cropland conversion. To simplify the experimental design, and to facilitate interpretation, we implement the post-harvest loss reduction experiment as a supplement to the baseline simulation – implemented subsequently on the updated, 2050 data base. This means that the percentage changes reported in Table 1 refer to changes, relative to the 2050 baseline. This is done for each of the two trade regimes (each of which produces a different 2050 baseline) – first in the presence of historically segmented markets, and then under the assumption of integrated commodity and factor markets.

Within the SIMPLE framework, the impact of improved storage technology in SSA is treated as a technological improvement which allows the same farm inputs to yield greater marketable output. Thus we abstract from the costs of achieving these reduced storage losses. This leads us to overstate the ensuing price decline, as well as the net social benefits from the technology. However, assuming these costs are the same under both trade regimes (both segmented and integrated markets), they cancel out when we focus on the differential impacts under market segmentation versus those under market integration. Furthermore, in this experiment, we assume that post-harvest losses in Africa (currently estimated to be 28%) are reduced to the level of Latin America (18%) (FAO, 2011). This implies that, in the absence of price-induced adjustments in supply and demand, 10% more domestically produced crops will become available for consumption in Africa.

The simulations reported in Table 1 show that, with segmented markets, the benefits in terms of lower food prices and improved nutritional outcomes are clearly concentrated in SSA, where crop prices are 9% lower and undernutrition is 12% lower in 2050 as a result of this improvement (Table 1, lower panel). Globally crop prices are little affected. Cropland area increases in SSA but at a negligible rate (+0.1%), with small declines in other regions. Globally, cropland and terrestrial carbon emissions from cropland conversion in 2050 are 0.3% lower as a consequence of the improvement in post-harvest storage technology in Sub Saharan Africa under segmented markets.

These results contrast sharply with those obtained under the assumption of full market integration (second entry in each pairing in Table 1). Now the benefits of increased crop availability in Africa are spread globally, so that prices in SSA (as well as international prices) fall by just −0.9%. Therefore, the nutritional gains in the SSA region are much more muted (just 1.8% as opposed to 11.5% reduction in non-farm undernutrition under segmented markets). In addition, cropland area and carbon emissions in SSA now rise as a result of the improved technology (5.9%). This may seem counterintuitive. However, the improved post-harvest handling of crops increases crop availability in the region and reduces prices. This causes SSA to reduce imports and increase exports. With integrated world markets, the entire world benefits from improved crop storage in Africa. Furthermore, as with the African Green Revolution experiment, since SSA cropland has a relatively low carbon emissions efficiency (low yields, relative to stock of terrestrial carbon released upon cropland conversion), strong expansion in this region at the expense of production in higher emissions efficiency regions results in a rise in global GHG emissions. In short, improved technology in Africa is more beneficial to food security and the environment in SSA under historically segmented markets.

3.4.3. *Reducing food waste in rich countries*

There are currently many government interventions being considered to reduce food waste in the EU and other wealthy regions (Parfitt et al., 2010). An important motivation for these initiatives is to lessen the global environmental burden of feeding the world's population. What effect, if any, will this have on the food and environmental security metrics considered in this paper? This will depend on the mechanism chosen for achieving the goal of less food waste – a point which is generally unclear in most proposals which simply 'mandate' a reduction or even the full elimination of waste (Delman, 2015). Some have advocated for regulatory interventions bearing on institutional food providers, mandating a reduction in food waste, but leaving the approach up to individual institutions (http://www.mass.gov/eea/agencies/massdep/recycle/reduce/food-waste-ban.html). And there are proposals to revise 'sell by' dates in grocery stores, and make safe, but dated produce available to food pantries (Duggan, 2016). Clearly all of these measures involve significant costs. As with the post-harvest loss reduction, we will ignore these costs, assuming they are the same under both international trade scenarios, and we will focus our attention on the difference between the two scenarios. We simulate the impact of reduced food waste by reducing the effective demand (a leftward shift in the demand schedule) for food in the richer countries, based on the assumption that food waste in each region (FAO, 2011) is cut in half.

The third row in Table 1 reports the impacts of reducing food waste on prices, undernutrition and terrestrial GHGs under the two market scenarios. All results are reported as percentage changes, relative to the 2050 baseline. In the case of segmented markets, the primary impact of reducing food waste in the developed economies is felt within those economies, resulting in reduced cropland conversion and conservation of terrestrial carbon. The impact on cropland use elsewhere, and non-farm undernutrition in the developing countries, is modest (−0.7% and −1.6%, respectively). This result is altered somewhat in the presence of globalization. Now the reduction of food waste in the developed economies reduces prices around the world and therefore contributes to a small global reduction in undernutrition (−1.5% relative to 2050 baseline). Cropland conversion in the rest of the world is also reduced, contributing to lower terrestrial CO2 emissions (−0.7%), worldwide. In short, the food and terrestrial impacts of reducing food waste in rich countries are not significantly altered by globalization.

3.4.4. *Impacts of REDD+ on food security and land-based emissions*

The fourth set of experiments which we undertake explores how globalization impinges on policies aimed at mitigating climate change. For this application, we draw on the work of Golub et al. (2012) who model the impact of a global carbon policy in which developed countries implement a comprehensive climate mitigation program – targeting fossil fuel emissions, as well as non-CO2 GHG emissions from industry and agriculture, in addition to carbon sequestration incentives for forestry. However, in their scenario, developing countries only pursue the REDD+ policy with payments for this program being covered by the rich countries. The price of carbon across all mitigation alternatives is $27/ton CO2e. Results are reported at the level of individual agro-ecological zones in each of their model regions (Appendix A5 in Supplementary materials). For purposes of this analysis, we aggregate their cropland cover shifts to the level of the 15 regions of SIMPLE and focus on the equilibrium change in global cropland area, as this is the main channel through which the terrestrial carbon policy affects the crops sector. Specifically, we consider the cropland cover shifts generated under scenario B in Golub et al. (2012). We then report the figures relative to the 2050 baseline without these policies. (Additional details on the Golub et al. (2012) study, and its use here, are available in the Appendix, Section A.6.)

The results at the global level show that the REDD policy results in modest upward pressure on crop prices and non-farm undernutrition in both segmented and integrated markets (Table 1, top panel). As intended, the policy is effective in mitigating environmental damages from agriculture. From the final columns in Table 1, we observe a large reduction in global cropland area and terrestrial carbon emissions (−11.4% and −15.1%, respectively, under segmented markets). Since REDD+ is implemented at global scale, the presence of integrated markets does little to change the food and environmental security metrics reported in Table 1.

Looking at the changes in SSA (bottom panel of Table 1), we see a somewhat higher percentage increase in non-farm undernutrition (3.3%), while cropland area and GHG emissions are reduced by a much greater percentage in SSA than at the global level. The SSA region has an ample supply of cropland and which could respond readily to changing market conditions in the presence of a global REDD+ initiative. Also, as previously noted, the SSA region has a relatively high ratio of terrestrial carbon to crop yields (West et al., 2010), so there are strong incentives to respond to REDD+ payments by setting aside forest lands. This results in less deforestation, relative to baseline, at the expense of reduced crop land area and production in 2050. Consequently, prices and non-farm undernutrition rise in the SSA region under both segmented and integrated markets. Indeed, market integration has little impact on the expected results from this REDD+ scenario.

3.4.5. *Impacts of climate change on food security and global land use*

The final scenario considered here is one in which the driving force is not policy-driven, but rather one which is dictated by environmental change. Much has been written about the potential impacts of climate change on agriculture (IPCC, 2014) and the IPCC recently convened a global summit to draw attention specifically to the food security aspects of climate change (Mastrandrea et al., 2015). Here, we draw on the archive of 36,000+ global, gridded climate impact runs provided by AgMIP (Rosenzweig et al., 2014) and accessed via GEOSHARE (Villoria et al., 2014, 2016) to identify one of the more comprehensive studies yielding a worst case scenario for agricultural impacts in 2050. Specifically, we use predictions from the LPJmL crop model (Bondeau et al., 2007) building on climate predictions from the HADGEM model (Bellouin et al., 2011), assuming no beneficial effects from elevated atmospheric CO_2 levels. (The latter remain a source of considerable controversy among crop scientists.) We pick this scenario, not because we believe it is the most likely one, but simply because it generates the most stress on the global food system with crop yields falling by 11% in SSA and 37% in South Asia. (The complete set of climate impacts on crop yields are available in

Appendix Table A3 in Supplementary materials. See also Baldos and Hertel (2015))

The impacts of this climate change scenario, relative to the baseline without climate change, are reported in Table 1. Global crop prices rise sharply as a result of the productivity set-backs in agriculture. Under segmented markets, non-farm malnutrition rises by 45.2% globally. The largest impacts are in South Asia, where the malnutrition headcount nearly doubles (see Appendix Table A2 in Supplementary materials). The striking feature of integrated markets is that it sharply curtails these adverse food security impacts in the hard-hit South Asia region, such that the global rise in malnutrition less than 30%. The reason for this beneficial effect of market integration is that the most severely affected region (South Asia in this case) is able to import food from the regions where climate change impacts are moderate – or even favorable for agriculture (see Appendix Table A2 in Supplementary materials). Since climate impacts in the SSA region are less severe under this scenario, it benefits relatively less from market integration, with food prices rising slightly more under integrated markets. The overall implications for terrestrial carbon are similar under the two trade regimes. In summary, market integration can significantly moderate the adverse food security impacts of climate change in the hardest hit regions of the world.

4. Discussion and limitations

There are many limitations to the analysis presented here. First and foremost is the relative simplicity of the model. Indeed, its very name – SIMPLE – indicates that it does not attempt to capture all of the complexity present in the global agricultural economy. We focus on one aggregate, composite crop, thereby abstracting from changes in crop composition over time and across policies. Nonland inputs are treated as a single factor of production which can be substituted for land to permit endogenous intensification, yet in reality these are made up of heterogeneous inputs, ranging from labor to capital and fertilizers.

The trade specification in this model is also a simplified one in which the initial shares in the Armington structure serve as a proxy for current levels of trade barriers. In many of the countries in Africa and South Asia, poor infrastructure and cumbersome customs procedures greatly inhibit trade. Rather than modeling these barriers explicitly, we simply allow them to be reflected in the very low observed trade share, leading to a low elasticity of price transmission from the international to domestic market. (This value is just 0.189 in the case of SSA, meaning that just 18.9% of an international price rise will reach local producers (Table A1 in Supplementary materials)). However, our historical simulations indicate that these relatively simple representations of production and consumption relationships allow us to reproduce key developments in global agriculture over the past half-century – particularly at global scale. (Regional predictions of crop output and land use are more challenging, as noted above.)

When we model globalization, we do so by changing the structure of the model to simply eliminate all trade barriers. It is highly unlikely that the world will get to this point by 2050. Trade and transport costs, as well as differential product standards, will likely continue to prevent the emergence of a single commodity price worldwide. However, by taking this specification to an extreme, we are able to more clearly see the implications of the ongoing trends toward globalization. Here, we appeal to Box (1976) who notes: “all models are wrong . . . .. The only question of interest is ‘is the model illuminating and useful’?” We believe that this simplified approach to examining the interplay between globalization on the one hand and food and environmental security on the other, is indeed illuminating.

5. Conclusions and policy implications

This paper has examined the food and environmental security implications of a range of policies affecting the global food system, first in the context of historically segmented markets, and secondly in a hypothetical future world of fully integrated crop commodity markets. While the latter scenario is unlikely in the near future, it is not impossible to imagine the emergence of a more smoothly functioning world agricultural marketplace by the middle of the 21st century.

Historically, restrictive agricultural trade policies in the wealthy economies, coupled with agricultural trade barriers and weak trade facilitation in many developing countries, have limited the volume of international trade in farm products, creating a situation whereby domestic and international prices are not constrained to move in tandem. This has meant that domestic sources of demand growth have been disproportionately important for local producers, and this market segmentation has served to protect agricultural producers with below-average productivity growth rates, such as those in much of Africa. This stands in sharp contrast with that of perfectly integrated world markets. In the latter case, all regions share the same global demand drivers and it is the *relative* rates of agricultural productivity, population and income growth that determine which regions expand farm production to meet these growing demands.

Before looking forward, we first engage in a retrospective analysis, asking the counterfactual question: how would food and environmental security have evolved over the period: 1961–2006 in the presence of greater market integration? We find that there would have been greater disparities in regional crop output growth, with those regions experiencing higher productivity growth over this period expanding more rapidly. Indeed, we estimate that crop output in North America would have grown much more rapidly under integrated markets, whereas output in Sub-Saharan Africa would have grown more slowly due to productivity growth rates well below the global average. While the greater exposure to global markets would have hurt farm households in Africa, the lower food prices would have significantly benefited urban consumers. In addition, by promoting more land conversion in regions with relatively high terrestrial emissions efficiencies, market integration would have lowered terrestrial carbon emissions over this period.

Going forward, greater market integration can be expected to reshape the way we think about future food security and terrestrial ecosystems. In the presence of lingering market segmentation, strong population growth in our baseline projections, accompanied by robust overall income growth projections in Sub-Saharan Africa, result in exceptionally high demand growth in the region. When accompanied by slow growth in SSA agricultural productivity, this translates into higher food prices for consumers, and higher levels of non-farm undernutrition in 2050. This underscores the potential importance of improved market integration for food security outcomes – particularly in the absence of improved productivity in African agriculture.

It is hard to predict how future productivity growth will evolve in the coming decades. Climate change is likely to serve as a drag on future productivity growth (IPCC, 2014). In this context, we show that greater economic integration serves as a sort of food security insurance against the most dire climate impact predictions. The climate change scenario considered in this paper was selected due to the severity of its impacts on crop yields in 2050–particularly in South Asia, where yields falls by 37%. This leads to a sharp increase in undernutrition in 2050 (97% in South Asia and 45% globally). However, in the presence of integrated markets, these increases are greatly moderated (34% and 27%, respectively). Given the uncertainty associated with global climate impact estimates, this is a strong argument for greater integration of global agricultural markets.

However, market integration brings with it some unexpected consequences. Of particular note are the impacts of ongoing efforts to enhance agricultural and post-harvest technology in Africa. In the current trade environment, with limited price transmission between global and local markets in SSA, these productivity-boosting investments can be expected to have a strong impact on local prices, reducing non-farm food insecurity and potentially reducing rates of cropland conversion. However, in a future, counterfactual world of crop market integration, these initiatives have a much more modest impact on local prices and non-farm undernutrition. And they may result in significant increases in cropland conversion and associated carbon emissions. In this globally integrated economy, protection of environmentally sensitive lands becomes a top priority.

Acknowledgements

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 as well as from USDA-NIFA project IND01053G2 and Hatch project 1003642.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.gloenvcha.2016.10.006.

References

Alexander, Peter, Rounsevell, Mark D.A., Dislich, Claudia, Dodson, Jennifer R., Engström, Kerstin, Moran, Dominic, 2015. Drivers for global agricultural land use change: the Nexus of diet, population, yield and bioenergy. Glob. Environ. Change 35 (November), 138–147. doi:http://dx.doi.org/10.1016/j.gloenvcha.2015.08.011.

Anderson, Kym, Rausser, Gordon, Swinnen, Johan, 2013. Political Economy of public policies: insights from distortions to agricultural and food markets. J. Econ. Lit. 51 (2), 423–477. doi:http://dx.doi.org/10.1257/jel.51.2.423.

Anderson, Kym, 2009. Distortions to Agricultural Incentives: A Global Perspective, 1955–2007. World Bank Publications, Washington, D.C., USA.

Agricultural technologies and tropical deforestation. In: Angelsen, A., Kaimowitz, D. (Eds.), Agricultural Technologies and Tropical Deforestation. CAB International.

Armington, Paul S., 1969. A Theory of Demand for Products Distinguished by Place of Production (Une Théorie de La Demande de Produits Différenciés D'après Leur Origine) (Una Teoría de La Demanda de Productos Distinguiéndolos Según El Lugar de Producción). Staff Papers (International Monetary Fund) 16 (1), 159–178. doi:http://dx.doi.org/10.2307/3866403.

Arvis, J.-F., Mustra, M.A., Ojala, L., Shepherd, B., Saslavsky, D., 2012. Connecting to compete 2012: trade logistics in the global economy. World Bank Other Operational Studies 12689. The World Bank. http://econpapers.repec.org/paper/wbkwboper/12689.htm.

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. Environ. Res. Lett. 8 (3), 34024. doi:http://dx.doi.org/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. Austr. J. Agric. Resour. Econ. doi:http://dx.doi.org/10.1111/1467-8489.12048.

Baldos, Uris Lantz, C., Thomas Hertel, W., 2016. Debunking the 'new normal': why world food prices are expected to resume their long run downward trend. Glob. Food Security 8 (March), 27–38. doi:http://dx.doi.org/10.1016/j.gfs.2016.03.002.

Bellouin, N., Collins, W.J., Culverwell, I.D., Halloran, P.R., Hardiman, S.C., Hinton, T.J., Jones, C.D., et al., 2011. The HadGEM2 family of met office unified model climate configurations. Geosci. Model. Dev. 4 (3), 723–757. doi:http://dx.doi.org/10.5194/gmd-4-723-2011.

Bondeau, Alberte, Smith, Pascalle C., Zaehle, Sönke, Schaphoff, Sibyll, Lucht, Wolfgang, Cramer, Wolfgang, Gertenr, Dieter, et al., 2007. Modelling the role of agriculture for the 20th century global terrestrial carbon balance global change. Biology 13 (3), 679–706. doi:http://dx.doi.org/10.1111/j.1365 -2486.2006.01305.x.

Box, George E.P., 1976. Science and statistics. J. Am. Stat. Assoc. 71 (356), 791–799. doi:http://dx.doi.org/10.2307/2286841.

Bureau, Jean-Christophe, Houssein Guimbard, and Sebastien Jean. 2016. "Competing Liberalizations: Tariffs and Trade in the 21st Century." Working Paper No. 2016-12. CEPII. May. http://www.cepii.fr/CEPII/en/publications/wp/abstract.asp?NoDoc=9116.

Burgess, R., Donaldson, D., 2010. Can openness mitigate the effects of weather shocks? Evidence from India's famine era. Am. Econ. Rev. 100 (2), 449–453. doi:http://dx.doi.org/10.1257/aer.100.2.449.

Burney, Jennifer A., Davis, Steven J., Lobell, David B., 2010. Greenhouse gas mitigation by agricultural intensification. Proc. Natl. Acad. Sci. 107 (26), 12052–12057. doi:http://dx.doi.org/10.1073/pnas.0914216107.

Davis, Kyle F., Gephart, Jessica A., Emery, Kyle A., Leach, Allison M., Galloway, James N., D'Odorico, Paolo, 2016. Meeting future food demand with current agricultural resources. Glob. Environ. Change 39 (July), 125–132. doi:http://dx.doi.org/10.1016/j.gloenvcha.2016.05.004.

Deininger, Klaus W., Byerlee, Derek, 2010. Rising Global Interest in Farmland: Can it Yield Sustainable and Equitable Benefits? The World Bank, Washington, D.C.

Delman, Edward, 2015. Should it be illegal for supermarkets to waste food? Atlantic 29 (May) . http://www.theatlantic.com/international/archive/2015/05/law-france-supermarkets-food-waste/394481/.

Duggan, Tara, 2016. Food waste is target of legislation on expiration labels. SFGate 24 (March) . http://www. sfgate. com/food/article/Food-waste-is-target-of-legislation-on-expiration -6975097.php.

European Commission, 2012. The Common Agricultural Policy: A Story to Be Continued. Publications Office of the European Union, Luxembourg.

FAO Statistical Database, 2015. Rome, Italy: Food and Agriculture Organisation of the UN. http://faostat.fao.org/.

FAO, 2011. Global Food Losses and Food Waste: Extent, Causes and Prevention. (Rome, Italy).

FAO, 2012. FAO Food Security Statistics. . http://www.fao.org/economic/ess/en/.

FAOSTAT, (2015). Food and Agriculture Organisation of the UN, Rome, Italy. Retrieved from http://faostat.fao.org/

Fugli, Keith O., 2012. Productivity growth and technology capital in the global agricultural economy. In: Fuglie, Keith O., Wang, Sun Ling, Eldon Ball, V. (Eds.), Productivity Growth in Agriculture: An International Perspective. CAB International, Cambridge, MA, USA, pp. 335–368.

Gale, Fred, 2013. Growth and evolution in China's agricultural support policies. Economic Research Report 153. USDA Economic Research Service, Washington, D.C. http://www.oryza.com/sites/default/files/err153.pdf.

Golub, Alla A., Henderson, Benjamin B, Hertel, Thomas W., Gerber, Pierre J., Rose, Steven K., Sohngen, Brent, 2012. Global climate policy impacts on livestock, land use, livelihoods, and food security. Proc. Natl. Acad. Sci. doi:http://dx.doi.org/10.1073/pnas.1108772109.

Hayami, Yujiro, Ruttan, Vernon W., 1985. Agricultural Development: An International Perspective. Johns Hopkins University Press, Baltimore.

Hertel, Thomas W., Baldos, Uris Lantz C., 2016. Global Change and the Challenges of Sustainably Feeding a Growing Planet. Springer International Publishing, New York. http://link.springer.com/10.1007/978-3-319-22662-0.

Hertel, Thomas W., 1997. Global Trade Analysis: Modeling and Applications. Cambridge University Press, New York.

Hertel, Thomas, Hummels, David, Ivanic, Maros, Keeney, Roman, 2007. How confident can we be of CGE-based assessments of free trade agreements? Econ. Model. 24 (4), 611–635.

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. Proc. Natl. Acad. Sci. 111 (38), 13799–13804. doi:http://dx.doi.org/10.1073/pnas.1403543111.

Hertel, T.W., Baldos, U.L.C., van der Mensbrugghe, 2016. Predicting Long Term food demand, cropland use and prices. Annual Rev. Resour. Econ. (forthcoming).

IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Johnson, D. Gale, 1973. World Agriculture in Disarray. Macmillan, London, UK; New York, USA.

Kaminski, Jonathan, Christiaensen, Luc, 2014. Post-harvest loss in Sub-Saharan Africa—what do farmers say? Global Food Security, SI: GFS Conference 2013 doi:http://dx.doi.org/10.1016/j.gfs.2014.10.002 3 (3–4).

Kriegler, Elmar, O'Neill, Brian C., Hallegatte, Stephane, Kram, Tom, Lempert, Robert J., Moss, Richard H., Wilbanks, Thomas, 2012. The need for and use of socio-economic scenarios for climate change analysis: a new approach based on shared socio-economic pathways. Glob. Environ. Change 22 (4), 807–822. doi:http://dx.doi.org/10.1016/j.gloenvcha.2012.05.005.

Lambin, Eric F., Meyfroidt, Patrick, 2011. Global land use change, economic globalization, and the looming land scarcity. Proc. Natl. Acad. Sci. 108 (9), 3465–3472. doi:http://dx.doi.org/10.1073/pnas.1100480108.

Lobell, D.B., Baldos, U.L.C., Hertel, T.W., 2013. Climate adaptation as mitigation: the case of agricultural investments. Environ. Res. Lett. 8. doi:http://dx.doi.org/10.1088/1748-9326/8/1/015012.

Ludena, Carlos E., Hertel, Thomas W., Preckel, Paul V., Foster, Kenneth, Nin, Alejandro, 2007. Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. Agric. Econ. 37 (1), 1–17. doi:http://dx.doi.org/10.1111/j.1574-0862.2007.00218.x.

Margulis, Matias E., McKeon, Nora, Borras Jr., Saturnino M., 2013. Land grabbing and global governance: critical perspectives. Globalizations 10 (1), 1–23. doi:http://dx.doi.org/10.1080/14747731.2013.764151.

Martin, Will, Winters, L. Alan, 1997. The Uruguay Round and the Developing Countries. Cambridge University Press.

Mastrandrea, Michael, et al., 2015. IPCC expert meeting on climate change, food, and agriculture. Meeting Report, IPCC Dublin, Ireland.

McCalla, A.F., Revoredo, C.L., 2001. Prospects for global food security: a critical appraisal of past projections and predictions. Food, Agriculture, and the Environment Discussion Paper 35. International Food Policy Research Institute, Washington D.C., USA.

Muhammad, Andrew, Seale Jr., James L., Meade, Birgit, Regmi, Anita, 2011. International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data. Technical Bulletin TB-1929. Economic Research Service, US Department of Agriculture, Washington, D.C., USA. http://www.ers.usda.gov/Publications/TB1929/.

Murdock, L.L., Baoua, I.B., 2014. On purdue improved cowpea storage (PICS) technology: background, mode of action, future prospectsJ. Stored Prod. Res. 58 (July), 3–11. doi:http://dx.doi.org/10.1016/j.jspr.2014.02.006. . (Hermetic Storage of Grain in Developing Nations) http://www.ers.usda.gov/Publications/TB1929/.

O'Neill, Brian, C., Kriegler, Elmar, Riahi, Keywan, Ebi, Kristie L., Hallegatte, Stephane, Carter, Timothy R., Mathur, Ritu, van Vuuren, Detlef P., 2014. A new scenario framework for climate change research: the concept of shared socioeconomic pathways. Clim. Change 122 (3), 387–400. doi:http://dx.doi.org/10.1007/s10584-013-0905-2.

Parfitt, J., Barthel, M., Macnaughton, S., 2010. Food waste within food supply chains: quantification and potential for change to 2050. Philos. Trans. R. Soc. Lond. B: Biol. Sci. 365 (1554), 3065–3081. doi:http://dx.doi.org/10.1098/rstb.2010.0126.

Phalan, Ben, Onial, Malvika, Balmford, Andrew, Green, Rhys E., 2011. Reconciling food production and biodiversity conservation: land sharing and land sparing compared. Science 333 (6047), 1289–1291. doi:http://dx.doi.org/10.1126/science.1208742.

Puma, Michael J., Bose, Satyajit, Chon, So Young, Cook, Benjamin I., 2015. Assessing the evolving fragility of the global food system. Environ. Res. Lett. 10 (2), 24007. doi:http://dx.doi.org/10.1088/1748-9326/10/2/024007.

Reilly, John, Hohmann, Neil, Kane, Sally, 1994. Climate change and agricultural trade: who benefits, who loses? Glob. Environ. Change 4 (1), 24–36. doi:http://dx.doi.org/10.1016/0959-3780(94)90019-1.

Rose, Steven K., Ahammad, Helal, Eickhout, Bas, Fisher, Brian, Kurosawa, Atsushi, Rao, Shilpa, Riahi, Keywan, van Vuuren, Detlef P., 2012. Land-based mitigation in climate stabilization. Energy Econ. 34 (1), 365–380. doi:http://dx.doi.org/10.1016/j.eneco.2011.06.004.

Rosenzweig, Cynthia, Elliott, Joshua, Deryng, Delphine, Ruane, Alex C., Müller, Christoph, Arneth, Almut, Boote, Kenneth J., et al., 2014. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. 111 (9), 3268–3273. doi:http://dx.doi.org/10.1073/pnas.1222463110.

Schmitz, Christoph, van Meijl, Hans, Kyle, Page, Nelson, Gerald C., Fujimori, Shinichiro, Gurgel, Angelo, Havlik, Petr, et al., 2014. Land-use change trajectories up to: insights from a global agro-economic model comparison. Agric. Econ. 45 (1), 69–84. doi:http://dx.doi.org/10.1111/agec.12090.

Stevenson, James R., Villoria, Nelson, Byerlee, Derek, Kelley, Timothy, Maredia, Mywish, 2013. Green revolution research saved an estimated 18 to 27 million hectares from being brought into agricultural production. Proc. Natl. Acad. Sci. 110 (21), 8363–8368. doi:http://dx.doi.org/10.1073/pnas.1208065110.

Suweis, Samir, Carr, Joel A., Maritan, Amos, Rinaldo, Andrea, D'Odorico, Paolo, 2015. Resilience and reactivity of global food security. Proc. Natl. Acad. Sci. 112 (22), 6902–6907. doi:http://dx.doi.org/10.1073/pnas.1507366112.

Swinnen, Johan, 2010. The political economy of the most radical reform of the common agricultural policy. J. Int. Agric. Trade Dev. 59 (2), 37–48.

Verma, M., Hertel, T.W., Diffenbaugh, N.S., 2012. Can economic integration help adapt to climate change? The case of US corn price volatility. Under Rev. Clim. Change .

Vermeulen, Sonja J., Campbell, Bruce M., Ingram, John S.I., 2012. Climate change and food systems. Annual Rev. Environ. Resour. 37 (1), 195–222. doi:http://dx.doi.org/10.1146/annurev-environ-020411-130608.

Villoria, Nelson B., Hertel, Thomas W., 2011. Geography matters: international trade patterns and the indirect land use effects of biofuels. Am. J. Agric. Econ. 93 (4), 919–935. doi:http://dx.doi.org/10.1093/ajae/aar025.

Villoria, Nelson, Elliott, Joshua, Choi, H., Zhao, Lan, 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.

Villoria, Nelson B., Elliott, Joshua, Müller, Christoph, Shin, Jaewoo, Zhao, Lan, Song, Carol, 2016. Rapid aggregation of global gridded crop model outputs to facilitate cross-disciplinary analysis of climate change impacts in agriculture. Environ. Model. Softw. 75 (January), 193–201. doi:http://dx.doi.org/10.1016/j.envsoft.2015.10.016.

WTO Regional Trade Agreements, 2016. WTO Regional Trade Agreements. World Trade Organization, Geneva, Switzerland. http://rtais.wto.org/UI/PublicMaintainRTAHome.aspx.

West, Paul C., Gibbs, Holly K., Monfreda, Chad, Wagner, John, Barford, Carol C., Carpenter, Stephen R., Foley, Jonathan A., 2010. Trading carbon for food: global comparison of carbon stocks vs. crop yields on agricultural land. Proc. Natl. Acad. Sci. doi:http://dx.doi.org/10.1073/pnas.1011078107.

Wise, Marshall, Calvin, Katherine, Thomson, Allison, Clarke, Leon, Bond-Lamberty, Benjamin, Sands, Ronald, Smith, Steven J., Janetos, Anthony, Edmonds, James, 2009. Implications of limiting CO2 concentrations for land use and energy. Science 324 (5931), 1183–1186. doi:http://dx.doi.org/10.1126/science.1168475.

World Bank, 2009. Awakening Africa's Sleeping Giant: Prospects for Commercial Agriculture in the Guinea Savannah Zone and Beyond. .

World Bank, 2015. Global Economic Monitor. . http://data.worldbank.org/data-catalog/global-economic-monitor.