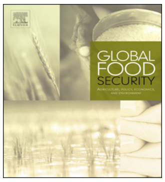
Global Food Security 8 (2016) 27–38

Contents lists available at ScienceDirect

Global Food Security

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



Debunking the ‘new normal’: Why world food prices are expected to resume their long run downward trend

Uris Lantz C. Baldos, Thomas W. Hertel*

Department of Agricultural Economics, Purdue University, 403 West State Street, West Lafayette, IN 47907, USA

ARTICLE INFO

Article history:
Received 6 November 2015
Received in revised form
7 March 2016
Accepted 17 March 2016

Keywords:
Long run crop prices
Food demand and supply
Agricultural productivity
Population growth
Income growth
Biofuels

ABSTRACT

Contrary to the opinions expressed by many commentators, the recent episode of higher prices for agricultural commodities is likely a transitory phenomenon. When compared to the last half-century, population growth is expected to be much slower in the coming decades, with nearly all of the growth occurring in lower income countries, where added population places less pressure on global markets. The impact of the recent surge in growth rates in the developing world, and the associated dietary upgrading, will be insufficient to overcome the population effect. Further, earlier projections of biofuels growth are proving overly enthusiastic in the wake of lower oil prices and environmental concerns. Consequently, our projections using the SIMPLE model of global agriculture suggest that, in the long run, food prices are expected to be slightly lower at mid-century than they were prior to the food price crisis (2006). However, this outcome is shown to depend critically on the rate of productivity growth in agriculture. Our projections involve expected global productivity growth over the 2006–2050 period which is only 60% as fast as over the historical period: 1961–2006. If total factor productivity growth slows more than this, perhaps due to adverse climate impacts or reduced investment in R&D, then prices could rise in the coming decades. Also, we cannot rule out the possibility of a steeper price decline in the wake of recent signs of robust productivity growth in the developing world.

1. Introduction

As recently as 2013, there appeared to be widespread agreement that international agricultural commodity prices had ceased their secular decline and were now on a new trajectory, owing to the emergence of large scale biofuel production, rapid growth in many developing economies, and slowing productivity growth. The World Bank (2013) stressed that “…high and volatile food prices have become the “new normal”…”. The Food and Agriculture Organization of the United Nations (FAO Media Centre, 2013) noted that “In the past century … real food prices declined steadily…. In the beginning of this century that long-term trend has been reversed…” The OECD/FAO (2013) stated that “prolonged periods of low agricultural prices driven by ever increasing productivity improvements… seem now a feature of a bygone era”. However, strong supply response in the 2014 crop year has subsequently altered this view of the world and the most recent OECD/FAO Outlook (2015) for the 2015–2024 period envisions modest price declines over the coming decade.

Nonetheless, there remains a strong belief that the future holds higher crop prices in store – particularly once climate change impacts and policies are factored into the analysis. Oxfam (2012) reported that “…the average price of staple foods… could more than double in the next 20 years compared with 2010 trend prices” in the wake of climate change. The International Food Policy Research Institute projected that the rise in the price of food grains such as rice, maize and wheat from 2010 to 2050 might be has high as 92% to 64% under current agricultural technologies (Rosegrant et al., 2014). A recent MIT study (Paltsev, 2012) suggests that global agricultural prices from 2010 to 2050 may increase by more than 20–30% if GHG mitigation policies are implemented. The idea that future commodity prices will rise continues to be pervasive in the public discourse.

We believe that the high price ‘consensus’ has been misguided. Observers were overly influenced by the 2007/08 and 2010/11 spikes in commodity prices, which, we believe, were largely driven by transitory phenomena, including record low stocks, an exceptional build-up in the U.S. and European Union biofuels programs, reactionary market interventions, and a succession of adverse weather events (Abbott et al., 2011; Piesse and Thirtle, 2009; Headey, 2010; Headey and Fan, 2010, 2008). Meanwhile, these studies have not paid sufficient attention to long run structural changes in the coming decades, including slowing population growth, the changing composition of global income growth and

---

* Corresponding author.
E-mail address: hertel@purdue.edu (T.W. Hertel).

http://dx.doi.org/10.1016/j.gfs.2016.03.002
2211-9124/

recent growth rates in agricultural productivity. When these underlying drivers of change are taken into account, we find that long run crop commodity prices will most likely resume a modest downward trend between now and 2050.

This is not the first time agricultural commodity prices have spiked over the past century. Fig. 1 reports CPI-deflated corn (grey squares), and aggregated grains (red) prices in the United States, which are broadly indicative of real agricultural commodity prices as a whole. In the early 1970s, food supply and trade shocks drove real food prices to levels not seen since the 1940s. However, over time, an expansion of supplies, coupled with the rebuilding of commodity stocks, led to prices resuming their long run downward trend. Indeed, Timmer (2010) has argued that regular food crises are to be expected every three decades as governments and private investors cycle through periods of low prices/disinterest in farming into periods of high prices and strong supply response. Is the recent experience with high prices just a repeat of the 1970s? Will prices resume their decline over the coming decades? In order to systematically explore this question, we report on a series of experiments designed to assess the long run changes in global food prices using the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE) (Baldos et al., 2013).

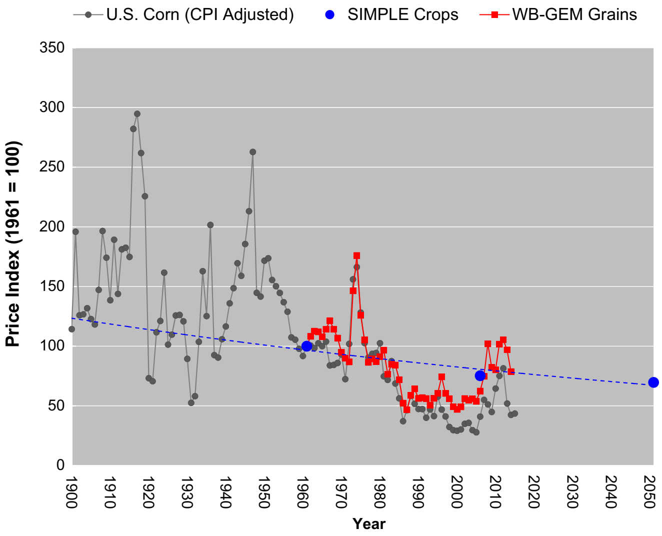


Fig. 1. Real crop prices: 1900–2051. Grey circles correspond to the historical evolution of annual U.S. corn prices from USDA-ERS Feed Grains: Yearbook Tables (US Department of Agriculture Economic Research Service, 2014), adjusted using estimated U.S. consumer price indices (CPI) from the Federal Reserve Bank of Minneapolis (2014). Red squares represent the global grain price indices from the World Bank – Global Economic Monitor (World Bank, 2015). Blue points report the historical and projected 45-year global crop prices based on simulations of the SIMPLE model for years 1961, 2006 and 2050. Blue dashed line connecting these points is a simple exponential trend line of these simulations based on the SIMPLE model.

The key elements of SIMPLE are laid out in Fig. 2. 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. Each regional crops sector is conceptualized as one in which land is combined with non-land inputs in order to produce crop output to satisfy domestic and global demands, including direct consumption, feedstuff demand, raw inputs to processed foods, and biofuel feedstock use. Food demands are price sensitive, and, over time, growth in food consumption is driven by population and per capita incomes. Rising incomes cause consumers to diversify their diets, which, at lower income levels, 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). Income also has an implicit effect on food demand response, as high income households typically spend less on food relative to non-food commodities; therefore, their demands are less responsive to changes in both income and food prices (Muhammad et al., 2011). In contrast, households in regions with low per capita incomes are more responsive to high food prices (i.e. larger absolute value for the price elasticity of demand), since food makes up a relatively large share of their budget. Additional crop demands in SIMPLE come from the exogenously specified feedstock use by the global biofuels industry.

On the supply side, substitution of non-land inputs (e.g., fertilizers, farm labor and machinery) for land in crop production offers scope for endogenous intensification of production, even in the absence of technological change. In addition, we allow for exogenous growth in agricultural productivity, driven by investments in

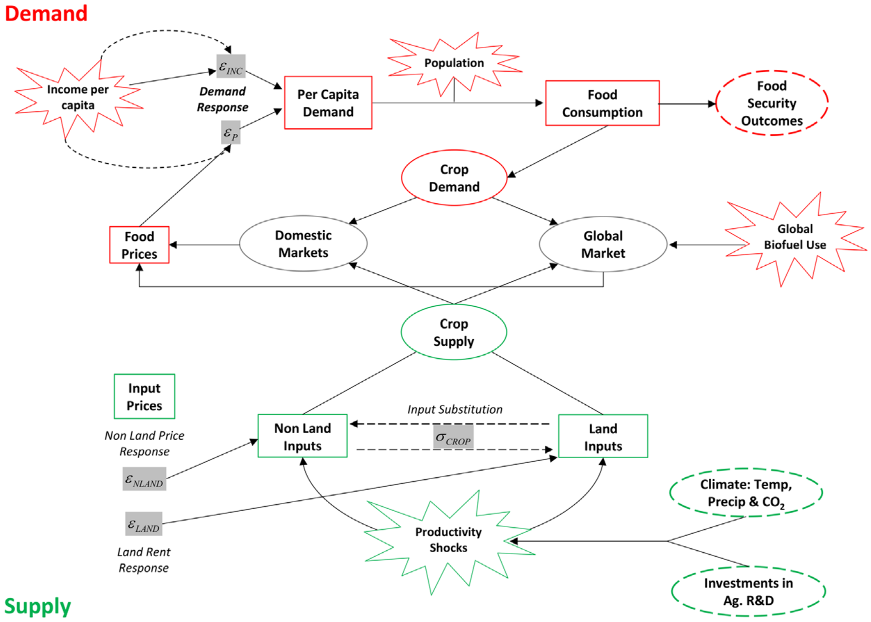


Fig. 2. Overview of the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE).

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 considerably across geographic regions. SIMPLE's historical projections of global crop production, area, yield and prices have been validated at global scale (Baldos et al., 2013) and the model has been used in studies focusing on climate change mitigation and adaptation (Lobell et al., 2013), long run food security analysis (Baldos et al., 2014) assessing the impact of green revolutions on land use and food security (Hertel et al., 2014), and for assessment of the interplay between climate change impacts and global trade (Baldos et al., 2015).

2. Historical analysis

To understand the future, one must first look back at history. We start by simulating the historical experience (i.e. 1961–2006) to examine how well the SIMPLE model reproduces the decline in global crop prices over this historical 45-year period (see also Baldos et al. (2013)). This historical simulation also allows us to assess the relative contribution of the major drivers of global agricultural prices. Growth rates for these historical drivers are calculated using population data from the U.N. World Population Prospects (2013) and real gross domestic product (GDP) data from the World Bank's World Development Indicators (2013). Productivity growth is represented by increases in total factor productivity (TFP) – an index of output per unit of a composite of all inputs. Historical TFP growth rates for the crop, livestock and processed food sectors are taken from Fuglie (2012), Ludena et al. (2007), and Griffith et al. (2004), respectively.

Over the 45 years leading up to the most recent commodity price boom, the World Bank's international index of food grain prices fell by more than 30% (Figs. 1 and 3). The SIMPLE model closely replicates this reduction and predicts a price decline of 35% based solely on historical growth rates in population, per capita income and agricultural productivity as reported in Table 1. The model also captures broad changes in historical crop output, crop yield and cropland use at the global level (Fig. 3).[1] For example, observed crop production rose by 204% over this period, while cropland expands by 12%. The SIMPLE model predicts a 180% output rise with a 13% expansion in cropland use. These results give us some confidence that we can use SIMPLE in order to simulate global long run changes in price, output, yield, and crop land at global scale.

While our main emphasis in this paper is on these global outcomes, it is also important to evaluate the performance of SIMPLE at regional scale. Early versions of this model had great difficulty reproducing regional patterns of output change due to the assumption of fully integrated world markets for crops (Baldos et al., 2013). This assumption flies in the face of historical experience in which trade and transport barriers limit access by many consumers and producers to world markets. Therefore the model used in this paper introduces *segmented domestic markets*, whereby domestic prices are not required to be equal to world prices, but are rather imperfectly connected with constant elasticities of substitution and transformation on the consumer and producer sides, respectively (Fig. 2). This allows for a better matching of simulated and observed regional output changes over the 1961–2006 period (Appendix Fig. A1). Of course, there remain significant differences, as the SIMPLE model excludes many important developments in agricultural markets over this period.

Table 1
Global average annual growth rates used in selected future scenarios.

Key drivers	Historical rates for key drivers	Future rates for key drivers + biofuels	"Low" price scenario	"High" price scenario
Population	1.71	0.78	0.56	1.02
Per capita income	1.44	1.90	0.73	2.80
Biofuels	–	3.88	3.04	4.72
Total factor productivity				
Crops[a]	1.50	0.86	1.04	0.46
Livestock[a]	0.82	1.16	1.16	1.16
Processed food	0.89	0.89	0.89	0.89

Notes:
Regional rates are published in (Appendix Table A1)
Historical population and income growth rates are taken from the 2012 UN World Population Prospects (2013) and World Bank's World Development Indicators (2013), respectively. Future rates use SSP2 projections from the SSP Database v0.5 projections (Kriegler et al., 2012; O'Neill et al., 2014). For Low ("High") price scenario, population growth rates are based on SSP1 (SSP3) projections while income growth is taken from SSP3 (SSP5) projections.
Biofuel growth rates are taken from the IEA's World Energy Outlook (2008, 2012). Future rates are based on *Current Policies* scenario 2012-40 p.a. rate. Under the Low ("High") price scenario, global biofuel growth is based from *Current Policies* scenario 2030-40 p.a. rate and *New Policies* scenario 2012-40 p.a. rate, respectively.
Historical TFP growth rates in the crop sector are taken from Fuglie (2012). Future rates are based on global TFP growth rates from Fuglie (2012) for the period 1961–2009 using regional scalars calculated from TFP rates for the period 1991–2009. For the "Low" ("High") price scenario, the global TFP growth rates are taken from Fuglie (2012) based on projected annual rates for the period 1991–2009 (1971–1990)
Historical and future TFP growth rates in the livestock sector are based on Ludena et al. (2007). TFP growth rate in the processed food sector is based on Griffith et al. (2004).

[a] Global TFP growth rates for the livestock and crop sectors are based on output value-weighted regional rates

An important feature of SIMPLE is that it allows for a decomposition[2] of the historical drivers of the global crop price index (colored areas in the third bar in each quadrant of Fig. 3). As can be seen from the red segments of the decompositions in Fig. 3, rising population was much more important than increasing per capita income over this historical period. Agricultural productivity growth (green segments in the third bar in each quadrant of Fig. 3) is a key driver of all variables, but is particularly important for yields and prices. Global yields for maize, rice and wheat increased by 1.8%, 2.0% and 2.2% annually (FAO, 2011). It is because productivity growth dominates the combined effect of population and income growth over this period, that crop prices fell (lower right hand quadrant of Fig. 3). A number of factors have helped contribute to the steady rise in crop yields, including development and adoption of new crop varieties, increased use of pesticides and fertilizers, and improved access to irrigation (Burney et al., 2010). Historical growth in potential yields (where yield potential is determined by the best available science) has averaged between 0.6 and 1.1.% annually for most crops, with the closing of gap between on-farm and potential yields accounting for the remaining portion of yield growth (Fischer et al., 2014).

---

[1] These are based on aggregate global changes using data from FAOSTAT (2014) between 1961 and 2006. Specifically, we use FAO data on global area of Arable land and Permanent Cropland as well as price-weighted global production for 135 crops.

[2] SIMPLE is implemented using the GEMPACK program (Pearson et al., 2000) which has many useful features for purposes of analysis. One of these is the subtotals feature developed by Harrison et al. (2000) which utilizes numerical integration techniques in order to exactly partition the impacts of different exogenous shocks on endogenous variables of interest.

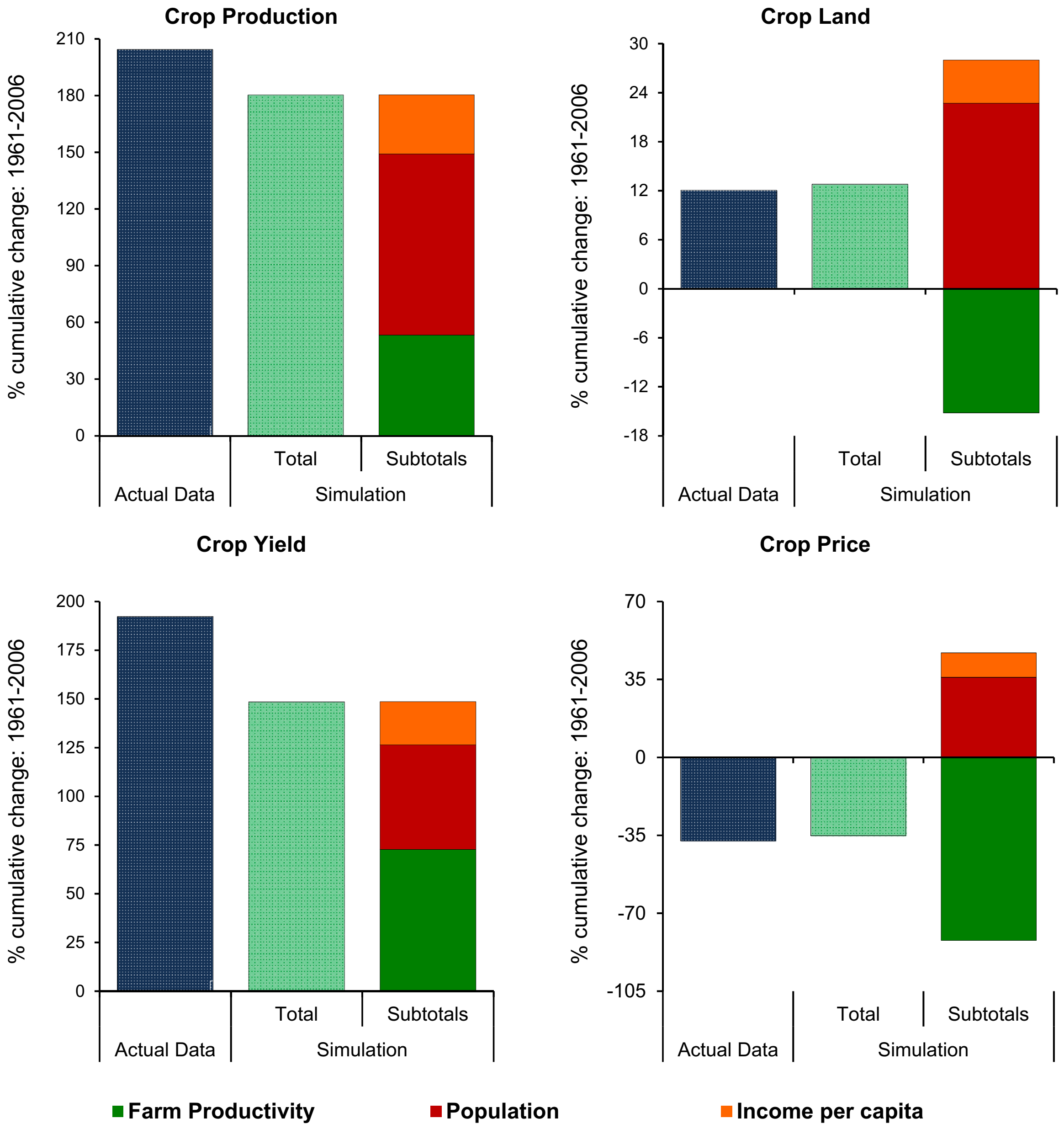


Fig. 3. Historical validation and decomposition of the drivers of global change in cropping: 1961 = 2006. Comparison of the observations (actual data) to the model simulations (total) shows how well the model reproduces historical changes. The simulated subtotals show the contribution of each of the three historical drivers to each model variable consisting of population (red area), per capita incomes (orange area) and agricultural productivity (green area).

3. Population and income: the main drivers of future food demand

As we look forward to 2051 (also a 45 year period), we find it useful undertake a series of experiments, each one adding additional information (Table 1 and Fig. 4). In this way we can better understand the drivers of global crop prices. We begin with what might be termed a 'naïve' forecast – namely one which assumes that historical growth rates for population, incomes and agricultural productivity will continue into the future. This comes about by applying the annual growth rates in the top panel of Table 1 to the observed 2006 economy, yielding a naïve projection of the global economy in 2050. (See Appendix Table A1 for detailed regional growth rates.) This results in the first bar reported in Fig. 4. Not surprisingly, a comparison with the historical change in crop prices over a comparable period shows that the relative contributions are the same as in the historical period. This result follows from the way we have designed our experiment, so it is hardly surprising that the percentage decline in the global crop price going forward is comparable to that in the historical simulation (around −32%). Of course, this is a poor prediction, since it does not avail itself of what we know about (e.g.) the impacts of declining fertility rates and slower growth in life expectancy in much of the world (Bloom, 2011; Ezeh et al., 2012).

The second bar in Fig. 4 adds the information provided by demographers about population growth from 2006–2051, taken from the Shared Socioeconomic Pathways (SSP) database (Kriegler et al., 2012; O'Neill et al., 2014). These projections are reported in the first row (Population) of the second panel of Table 1. While the predicted rise in world population to 9+billion in 2050 will still place additional pressure on world food production, the slower *global growth rate* means that population growth will have less impact on future food prices than it had over the 1961–2051 period, as shown by the smaller red area in the second bar of Fig. 4.

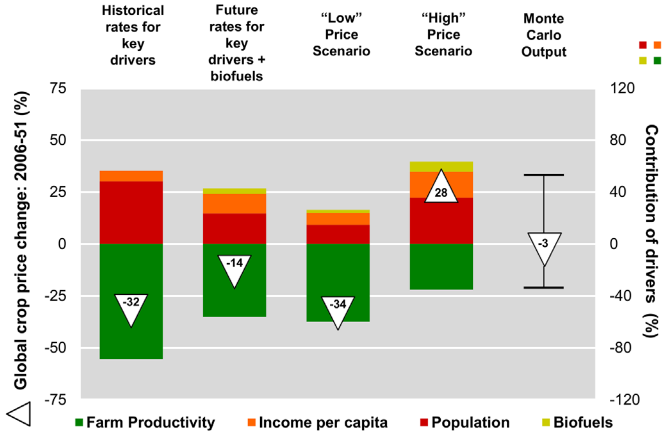


Fig. 4. The future of global crop prices: projection and decomposition. Long run changes in crop prices are read off the left-hand axis and % contribution of drivers of change are read off the right hand axis. These figures describe results for the period 2006 to 2051. These projections include (from left to right): continuation of historical growth rates for key drivers, our baseline with future growth rates for key drivers plus biofuels, bounding analysis showing both a "low price" scenario and a "high price" scenario, and finally, the mean price change and 95% confidence interval [−23%,30%] from a Monte Carlo analysis in which both model parameters and drivers are varied. Drivers include population (red area), per capita incomes (orange area), agricultural productivity (green area) and biofuels (tan area). The bounding analysis is constructed using min-max assumptions on population, income and agricultural productivity growth.

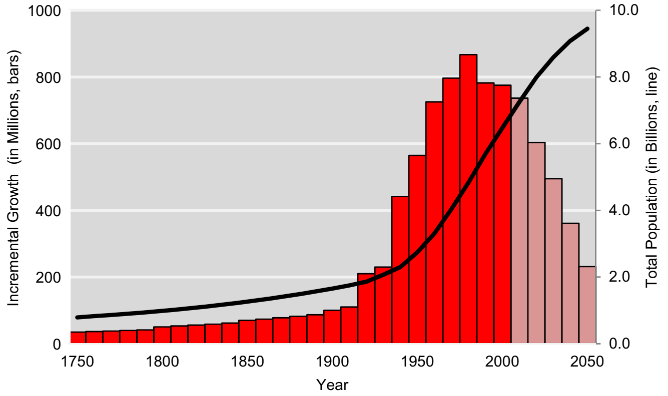


Fig. 5. Decadal increments (10-year average) vs. Total global population (annual), 1750–2050. 5 (2012; 2014) (light red bars). Source: UN Population Division 2000; 2013) (bright red bars) SSP Database v0.5 (Kriegler et al., 2012; O'Neill et al., 2014) (light red bars)

A useful means of portraying the diminishing impact of population growth on the global demand for food is to plot the observed/predicted decadal increments to population. This is shown in Fig. 5, where we see that, by this measure, the impact of population growth peaked in the 1980s and has been falling since then. By 2040s, the decadal increment to global population will be roughly the same as during the 1930s.

Another, more subtle reason why population's impact on global food prices is diminishing has to do with the geographic composition of global growth. This can be seen by comparing the regional composition of historical and future population growth rates in Table A1. In the latter half of the 20th century, population growth was still robust in much of the developed world. However, since then it has slowed markedly and is even declining in some of the rich countries (e.g., Eastern Europe, Japan and Korea). On the other hand, fertility rates remain as high as 7 children/woman in the poorest countries of West Africa (e.g., Niger), leaving the African continent poised to account for 50% of global population growth over the 2010–2050 period, even though it currently accounts for just over 15% of global population (Bloom, 2011). Adding an additional consumer in Niger has a much more modest impact on global consumption and resource requirements than adding an additional consumer in Germany. This means that population alone as a driver of global consumption is even less important than one might have thought from simple inspection of Fig. 5.

Even as the role of population as a driver of global food demand is diminishing in significance, per capita income growth is becoming more important. This is reflected in a comparison of the per capita income growth rates for the historical and future panels in Appendix Table A1. In South Asia, projected income growth is more than twice as rapid in the future period, reaching more than 5%/year. Income growth rates are also projected to be significantly higher in Africa and Central Asia (Fouré et al., 2013). Rapid growth in these countries where much of the population still has unmet dietary needs translates into strong increases in per capita consumption as well as changes in the mix of foods consumed. Per capita consumption of meats and dairy products is expected to rise as diets are upgraded and diversified (Cranfield et al., 2002). Indeed, this dietary upgrading has contributed significantly to the growth in global agricultural demands in recent years (Pingali, 2007) and rapid income growth in the developing world has been an important element of recent projections of higher commodity prices (Nelson et al., 2010; OECD/FAO, 2013). We find in our projections that nearly all the growth in volume of food consumption comes in the form of livestock and processed food products (Appendix Fig. A2).

The second bar in Fig. 4 shows that the contribution of projected future income growth (orange area) is projected to rival that of population (red area) for the first time in history if current trends continue. However, it is also the case that as lower income regions become wealthier, the responsiveness of food consumption to additional income increments is diminished (Muhammad et al., 2011) and studies which do not factor this into their projections will inevitably overstate the potential for future demand growth (Baldos et al., 2013). Thus, even with income becoming an equally significant driver of future food demand as population, this driver is not strong enough to compensate for the slower population growth. Therefore, assuming the same rate of productivity growth as observed from 1961 to 2006, we would expect long run crop prices to fall even more rapidly than over that historical period.

4. Biofuels as a driver of future demand

The remarkable growth in biofuels demand over the past decade has also contributed to analysts' expectations that world food markets have entered a "new normal". Indeed over the two crop year period from 2005/06–2007/08, half of the global increase in cereals consumption was absorbed by U.S. ethanol production (Westhoff, 2010). Similarly, one-third of the increase in vegetable oil use from 2004 to 2007 is estimated to have gone into biodiesel production (Mitchell (2008), cited in Piesse and Thirtle (2009), p. 127). There is little doubt that growth in first generation biofuels – namely those that utilize food crops as feedstocks – has contributed to higher crop prices over the past decade (Abbott et al., 2011) and many studies suggest that biofuels will place significant pressures on future crop demand and prices (Fischer et al., 2009; Msangi et al., 2010; Piesse and Thirtle, 2009; Headey and Fan, 2010, 2008). Whether or not these projections are realized depends critically on oil prices. Some studies suggest that corn ethanol production would continue to expand, even without government support, as long as oil prices remained above $100 (Miranowski and Rosburg, 2013; Tyner, 2008). However, recent increases in oil and gas supplies, as well as a slowdown in growth rates in the emerging economies, have precipitated a sharp drop in oil prices and suggest that earlier projections of rising energy prices (U.S. Energy Information Administration, 2013) were misleading. Indeed, as of the writing of this paper, the futures price in 2024 is only about half the $100/bbl. threshold for corn ethanol profitability.

In the absence of strong growth in oil prices, subsidies and mandates become critical to the growth of the biofuel industry. However, government support for this industry has been eroded due to concerns about the global environmental impacts of indirect land use change induced by biofuels (Searchinger et al., 2008; National Research Council, 2011). As a consequence, the current trend in Europe and the U.S. has been to trim back such support in the face of budget austerity and concerns about competitiveness (Babcock, 2013; European Commission, 2012). In the US, the EPA views the ethanol 'blend wall' as a significant barrier to further expansion and has therefore capped the ethanol mandate at 14 billion gallons/year in 2016 (US EPA, 2015). The European Commission has proposed to scale back by half the maximum contribution in 2020 of first generation biofuels to liquid fuels in the EU, favoring instead cellulosic biofuels (Junker et al., 2015). While these so-called second generation biofuels are sometimes favored since they are used in the food system, they nonetheless compete with food crops for scarce land, labor, capital and other farm inputs. Since they offer significant GHG savings over conventional fuels (National Research Council, 2011), they are likely to be significantly affected by future greenhouse gas (GHG) mitigation policies. However, these biofuels are not yet commercially viable, and most studies do not envision them playing a significant role for several decades (Rose et al., 2012; Steinbuks and Hertel, 2013).

In short, it is hard to predict how biofuel demands will evolve in the coming decades. Accordingly, in our baseline we opt for the 'business as usual' projections of biofuel growth by the International Energy Agency (IEA, 2014). Among the scenarios available, we use those generated under the 'Current Policies' scenario which takes into account all policies enacted as of mid-2014 (Table 1, Biofuels row). However, we do consider other scenarios in our subsequent Monte Carlo analysis (Appendix Table A2). From Fig. 4 it can be seen that, under the current policies scenario, biofuels add modestly to our baseline projections of future crop demand (tan area at the top of the second bar), thereby slightly bolstering crop prices by 2051.

5. Agricultural productivity remains a key to food prices and output growth

As in the past, agricultural productivity will play a key role in shaping future crop prices. If historical productivity growth rates were to continue into the future, food prices would most certainly fall, given the more modest rate of population growth projected to 2051, as well as the 'current policies' biofuels scenario from the IEA. However, projecting future productivity growth is extremely challenging. Part of the problem is that – unlike population and income, which are directly observable, agricultural productivity is fundamentally *unobservable*. Furthermore, there is no consensus about how productivity growth has evolved over the last two decades. Studies focusing solely on yield growth – a partial measure of productivity growth which focuses only on land and ignores the role of other farm inputs – find that the growth of yields for staples are slowing in key regions (Alston et al., 2009, 2010). However, yield growth rates are also sensitive to prices and it is not uncommon to observe moderating yield growth, even as TFP growth rates continue to rise strongly (Ludena et al., 2007). This is especially likely following long periods of depressed or flat world prices, as was the case from 1980 to 2005, or in the wake of domestic policy reforms resulting in lower producer prices, such as those implemented in Europe over the past two decades. Therefore it should not be surprising that studies focusing on Total Factor Productivity (TFP) growth come to rather different conclusions than the yield studies. Fuglie (2012), Table 16.3 reports an acceleration of TFP growth over the 1991–2000 period, even as the rate of growth of global cereal yields declined.

It is widely acknowledged that a key factor in sustaining long run productivity growth in agriculture will be investments in research and development (R&D). The global growth rate of public investments in agricultural R&D in high income countries fell somewhat over the 1990s (Pardey et al., 2006, as cited in Piesse and Thirtle, 2009, p. 125), but recent data suggests that it has picked up strongly since then, with global public and private R&D both rising by roughly one-quarter over the 2000–2008 period (Beintema et al., 2012). There has also been a shift in the pattern of investments, as R&D expenditures have grown faster in developing countries – particularly in Brazil, China and India. Yet despite the growth in other regions, more than half of global spending in agricultural research still comes from high income countries wherein the growth rates of R&D expenditures have continued to show signs of slowing. And the increasing reliance on private sector R&D (Pardey et al., 2006) raises questions about the future spillover benefits from this research. Finally, it should be notes that R&D expenditures in richer countries increasingly emphasize environmental and food safety concerns, as opposed to supply-enhancing measures.

The effectiveness with which R&D expenditures translate into productivity growth will hinge in part on climate change. Depending on the location, management practice, and crop type, temperature and precipitation impacts of climate change may cause potential crop yields to rise or fall (Tubiello et al., 2007). Between the two, temperature changes transmit the strongest signal in the context of agricultural impacts (Lobell et al., 2011; Schlenker and Lobell, 2010), with projected increased frequency and intensity of extreme heat events having a significant adverse impact on crop yields (Schlenker and Roberts, 2009). Recent estimates suggest that warming temperatures have slowed yield growth for wheat and maize over the past three decades, while mixed impacts on rice and soybeans have been offsetting at the global scale (Lobell et al., 2011).

Another aspect of climate change which could significantly affect agricultural productivity and global food availability is the presence of heightened CO_2 concentrations in the atmosphere. This can directly benefit crop yields through increases in leaf CO_2 levels and reductions in stomatal conductance, thereby boosting the optimum temperature for C3 crops (Long, 1991). However, these CO_2 impacts differ widely across crop types as well as agro-climatic conditions. And capitalizing on the elevated CO_2 levels depends on the availability of adequate nutrients – an assumption which does not apply in many developing countries. Moreover, analyses at the regional level show that CO_2 fertilization effects are quite uncertain as the variations in these impacts could be more than half of the variations from temperature and precipitation (McGrath and Lobell, 2013). Overall, most climate/crop model combinations show modest impacts – and indeed sometimes gains

– when it comes to crop supplies between the present and 2050 (Rosenzweig et al., 2013). It is only after mid-century, as temperatures continue to rise and CO_2 fertilization effects taper off, that the ensemble of climate-crop models show larger, more systematic declines in yields across all regions (IPCC, 2014).

Increasing water scarcity is another factor cited by authors predicting the emergence of a 'new normal' in commodity markets (Rosegrant et al., 2002). Assuming continued demand growth and no efficiency gains in water use, it has been estimated that one-third of the world's population will live in river basins where demand exceeds accessible, reliable supply by 50% or more (McKinsey & Co, 2009). One response to surface water scarcity in agriculture has been to turn to ground water, which has become an increasingly important source of irrigation over the past 50 years (Burke and Villholth, 2007). This growth has been most pronounced in areas with low recharge rates (Döll and Fiedler, 2007), thereby raising concerns over long run sustainability. In light of the fact that 40% of global crop production comes from irrigated lands, this suggests that water scarcity could indeed be a significant constraint on future supplies. Rosegrant et al. (2013) examine this issue in considerable detail, using a global water model. The authors estimate the Irrigation Water Supply Reliability (IWSR) index in 2000, 2030 and 2050 which depends on growth in food demand, changes in irrigation efficiency, changes in non-agricultural water use, water policies and infrastructure development. Their findings suggest that the IWSR does indeed deteriorate in a number of important river basins – particularly in South Asia and China. However, the large changes are limited to a few river basins, and their global impact is further mitigated by improvements in IWSR elsewhere. Accordingly, the subsequent impacts on world crop prices has been estimated to be quite modest (Liu et al., 2014). Thus water shortages, while critically important at the local and regional level, appear to be less important when it comes to long run global agricultural supply over the next few decades.

A final source of supply-side uncertainty relates to the potential for closing existing yield gaps, which are particularly pronounced in Sub Saharan Africa, Eastern Europe and parts of Latin America and Asia (Foley et al., 2011). These differences, which can be characterized as the differences between observed yields at a given site and maximum yields obtained under similar agro-ecological circumstances elsewhere in the world, are driven by economic factors in many cases (Herdt, 1979). These can include limited availability of locally-adopted technologies and poor access to markets which leads to high input costs and low output prices. Production risks can also hamper the adoption of existing technologies amongst subsistence farmers (Evans, 1993; Herdt, 1979). In addition, narrowing most of these gaps entails increased fertilizer use which could potentially lead to adverse environmental impacts if proper nutrient management is not practiced (Mueller et al., 2012). But if these gaps can be closed in an economical and sustainable way then this could provide a much needed opportunity to sharply increase global crop production in the future. Indeed, it has been estimated that global production of maize, wheat and rice could be increased by 29% if yields in underperforming areas are increased to 75% of yields in productive areas with similar agro-climatic conditions (Mueller et al., 2012).

In concluding this section, it is useful to refer back to the comprehensive review of historical and likely future growth rates for yields of maize, wheat, rice and soybeans, provided by Fischer et al. (2014). These authors separately project changes in potential yield and yield gaps – where the latter is defined as the difference between potential yield and farm yields, divided by farm yields. Historically, changes in potential yields have dominated global yield growth. However, progress here is becoming increasingly difficult, as the increases in the rate of interception of photosynthetically active radiation and the harvest index approach their biophysical limits. These authors argue that increases in radiation use efficiency still offer significant opportunities for increased potential yields, but that these will take time. This leads them to emphasize the role of *yield gap closing* in maintaining global crop yield growth rates over the next few decades. They conclude that global average growth rates in excess of one percent/year for staple yields are feasible, but will require sustained investment in research and development, as well as extension to promote adoption of the new technologies (Fischer et al., 2014).

The fourth row in each panel of Table 1 reports the historical/future projected rate of TFP growth in the SIMPLE model. Keith Fuglie's (2012) estimates of agricultural TFP growth over the 1961–2012 period which were used in the historical analysis imply an annual growth rate at global scale of about 1.5%/year (Table 1). Projected global TFP growth over the 2006–2050 period is taken from Ludena et al. (2007) and is only about 60% as fast (0.86%/year: Table 1). Factoring in these slower TFP growth rates, We obtain the projected crop price change shown in the second bar of Fig. 4 (−14%). It should be noted that our choice of base period, 2006, is immediately prior to the commodity price boom of the past decade, so a price drop from this level is a more substantial decline than from current levels (Fig. 1). Of course, as we have seen in this section, there is great uncertainty about the future of agricultural productivity growth and this suggests the importance of undertaking a formal uncertainty analysis of the future of global crop prices.

6. Assessing uncertainty in future commodity prices

The most straightforward approach to addressing the uncertainty in long run crop prices involves 'bounding analysis', the results of which are reported in the fourth and fifth columns of Fig. 4. The third bar in that figure reports a 'low price' future in which population and income growth is at the low end of future projections, and TFP growth is at the high end of likely outcomes, based on evidence over the past half-century. In this case, crop prices fall at the same rate as in the previous 45 year period (−34%) and there is virtually no incentive to expand crop land or intensify production at the global scale. On the other hand, if population and income growth is at the upper end of future projections and crop TFP growth is at the lower end (again, based on experience since 1961), then crop prices will rise modestly (28%) over the 2006–2051 period (Fig. 4, fourth bar). In this case, there is greater incentive to expand crop area and intensify the use of non-land inputs.

We have also undertaken a Monte Carlo analysis which offers a more systematic assessment of uncertainty by sampling simultaneously from distributions of the economic parameters as well as from distributions of the exogenous drivers (Hertel et al., 2016). The final bar in Fig. 4 reports the mean price change (−3%) from this Monte Carlo analysis. The associated 95% confidence interval (dotted line) shows that we cannot rule out the possibility of significant long run price increases, as observed under our high-price bounding scenario. However, these outcomes are the result of scenarios in which demand drivers and consumption responses to growth are at the high end of their distributions and supply side factors are at the low end. To assess the overall likelihood of price rises or declines, we construct a distribution of global crop price changes from the Monte Carlo simulations. The median value of the price decrease is −5% and, while there is a non-negligible probability that prices in 2051 will be higher than 2006, almost two-thirds (65%) of the outcomes lie on the negative side of the price change. This substantiates our claim that, as portrayed by the dotted projections line in Fig. 1, *in the long run, crop prices are most likely to resume a downward trend, albeit slower than in the historical period*.

7. Conclusions

In order to understand the future, it is important to study history, and the food crisis of the 1970s offers a valuable perspective on the current state of affairs. In the wake of this earlier crisis, Don Paarlberg (1981) coined the term “Scarcity Syndrome” to characterize mood prevalent at the time. His words are remarkably *apropos* to today's environment:

> “Pessimism has arisen about the ability of the Earth to feed its people. Burgeoning population growth…doubts about the adequacy of the agricultural resource base…allegations that discovery of new agricultural knowledge is lagging…misgivings about weather in the years ahead are cited in outlining a dismal food prospect for the poor people of the world.” (excerpt from the 1981 USDA Yearbook of Agriculture, entitled: ‘Will there be enough food?’, p 282)

Paarlberg's response to this perceived crisis was concisely summarized in the title to his chapter, which was: “Enough food? Sure, if we don’t play it dumb!” He believed that the global food economy would respond to the high prices of the 1970s with increased supplies, and this belief was, in fact, borne out by a prolonged period of declining/flat food prices over the next two decades.

We believe that the apparent consensus that the recent spike in crop prices will persist over the coming decades is unfounded and is excessively influenced by a ‘scarcity syndrome’ similar to that noted 30 years ago by Don Paarlberg. Rather, we expect that global food prices will most likely resume a modest downward trend in the coming decades and indeed we have observed a steady decline after 2014. However, analysis with the SIMPLE model of long term, global supply and demand for crops suggests that the factors behind this price decline will be different in the future. Looking back at history, we see that the increase in food demand was fueled mainly by population growth. This period was also characterized by strong agricultural productivity growth which led to significant gains in food production. Moving forward to mid-century, our analysis suggests that, despite expectations of slower productivity growth, as well as the rising importance of income growth in the world's poorest countries, and the increasing use of crops for biofuels in our baseline, global food prices will most likely be lower a mid-century than they were prior to the food crisis of 2007/8. This is largely due to the slowdown and changing regional composition of global population growth.

We recognize that there is tremendous uncertainty surrounding future food price trends, and we therefore provide a bounding analysis wherein we vary the growth rates of population and agricultural productivity – the main historical drivers of food demand and supply. With high population growth and a stagnation of TFP growth in the crops sector, food prices will indeed rise in the future. In contrast, slower population growth and faster crop TFP growth will result in even lower food prices, declining as fast as that observed reduction from 1961 to 2006. Our Monte Carlo analysis in which both model parameters and long run drivers are systematically varied reveals that two-thirds of the possible future outcomes show declining food prices between 2006 and 2051. Thus, we conclude that current expectations of rising long run food prices are misplaced and are likely motivated by extreme assumptions regarding the future trends in key drivers of global agriculture.

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. Valuable comments were received by two anonymous reviewers as well as participants in seminars at Purdue, Stanford, the University of Nebraksa, and meetings of the AAEA, AARES and the Global Land Project.

Appendix

(See Appendix Fig. A1 and Fig. A2 and Table A1, Table A2, and Table A3).

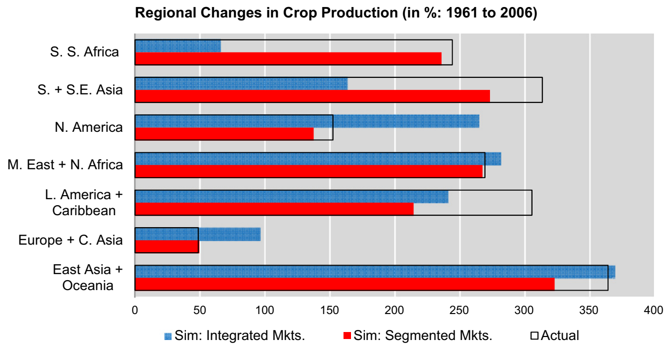


Fig. A1. Historical validation of regional crop production (1961–2006).

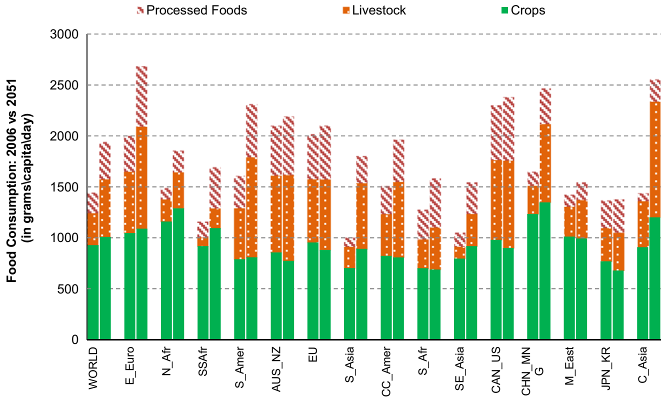


Fig. A2. Food consumption in 2006 and in 2051.

Table A1
Average annual growth rates used in selected scenarios.

	Regions															
Scenarios	Eastern Europe	North Africa	Sub Saharan Africa	South America	Australia/New Zealand	European Union+	South Asia	Central America	Southern Africa	Southeast Asia	Canada/US	China/Mongolia	Middle East	Japan/Korea	Central Asia	[a]World
Historical simulation (Historical rates for key drivers)																
Population	0.46	2.61	2.77	2.06	1.46	0.43	2.20	2.29	2.34	2.25	1.03	1.62	2.27	0.87	2.43	1.71
Per capita income	−1.72	1.33	−0.42	1.38	1.94	2.46	2.32	1.69	0.36	3.15	2.19	6.78	2.37	3.42	−2.49	1.44
Biofuels																
Total factor productivity																
Crops	0.37	1.97	0.71	1.70	1.43	1.58	1.16	0.97	1.38	1.50	1.70	2.02	1.61	2.11	0.37	1.50
Livestock	0.58	0.17	0.39	0.80	0.92	0.92	0.53	0.80	0.39	0.86	0.92	0.86	0.17	0.92	0.58	0.82
Processed food	0.89															0.89
Future rates for key drivers+biofuels																
Population	−0.32	0.96	2.23	0.71	0.79	0.03	0.90	0.89	0.41	0.73	0.58	−0.12	1.33	−0.35	1.07	0.78
Per capita income	2.93	2.95	4.02	2.58	1.26	1.11	5.17	2.15	2.94	3.86	0.99	5.23	1.71	1.58	4.28	1.90
Biofuels																3.88
Total factor productivity																
Crops	1.22	1.16	0.13	1.13	0.39	0.54	0.73	0.73	0.92	1.14	0.88	1.07	0.49	0.94	1.22	0.86
Livestock	1.05	0.43	0.43	2.37	0.43	0.43	1.71	2.37	0.43	2.37	0.43	2.37	0.43	0.43	1.05	1.16
Processed food	0.89															0.89
"Low" price scenario																
Population	−0.44	0.72	1.76	0.49	0.86	0.11	0.65	0.64	0.20	0.53	0.66	−0.23	1.08	−0.28	0.79	0.56
Per capita income	1.95	1.78	2.11	1.43	1.04	0.81	3.48	0.96	2.01	2.42	0.90	3.79	1.08	1.04	2.84	0.73
Biofuels																3.04
Total factor productivity																
Crops	1.46	1.39	0.17	1.35	0.48	0.66	0.89	0.89	1.11	1.37	1.06	1.28	0.60	1.14	1.46	1.04
Livestock	1.05	0.43	0.43	2.37	0.43	0.43	1.71	2.37	0.43	2.37	0.43	2.37	0.43	0.43	1.05	1.16
Processed food	0.89															0.89
"High" price scenario																
Population	−0.18	1.28	2.70	1.06	0.18	−0.41	1.21	1.40	0.68	1.02	−0.02	0.04	1.57	−0.56	1.51	1.02
Per capita income	3.73	3.78	5.40	3.40	1.56	1.45	6.21	3.01	3.78	4.80	1.26	6.07	2.60	2.03	5.31	2.80
Biofuels																4.72
Total factor productivity																
Crops	0.67	0.63	0.07	0.61	0.20	0.27	0.38	0.38	0.49	0.62	0.46	0.58	0.25	0.50	0.67	0.46
Livestock	1.05	0.43	0.43	2.37	0.43	0.43	1.71	2.37	0.43	2.37	0.43	2.37	0.43	0.43	1.05	1.16
Processed food	0.89															0.89

Notes:

Historical population and income growth rates are taken from the 2012 UN World Population Prospects (2013) and World Bank's World Development Indicators (2013), respectively. Future rates use SSP2 projections from the SSP Database v0.5 projections (Kriegler et al., 2012; O'Neill et al., 2014). For Low ("High") price scenario, population growth rates are based on SSP1 (SSP3) projections while income growth is taken from SSP3 (SSP5) projections.

Biofuel growth rates are taken from the IEA's World Energy Outlook (2008, 2012). Future rates are based on *Current Policies* scenario 2012-40 p.a. rate. Under the Low ("High") price scenario, global biofuel growth is based from *Current Policies* scenario 2030-40 p.a. rate and *New Policies* scenario 2012-40 p.a. rate, respectively.

Historical TFP growth rates in the crop sector are taken from Fuglie (2012). Future rates are based on global TFP growth rates from Fuglie (2012) for the period 1961–2009 using regional scalars calculated from TFP rates for the period 1991–2009. For the "Low" ("High") price scenario, the global TFP growth rates are taken from Fuglie (2012) based on projected annual rates for the period 1991–2009 (1971–1990)

Historical and future TFP growth rates in the livestock sector are based on Ludena et al. (2007). TFP growth rate in the processed food sector is based on Griffith et al. (2004).

[a] To facilitate comparison across scenarios, global growth rates for population, per capita incomes and TFP in the livestock and crop sectors are added in the table

Table A2
Uncertainty ranges for global drivers and economic parameters in SIMPLE.Sources of exogenous growth rates for global drivers are as follows.

Exogenous shocks (p.a. rates)	Mode	Max	Min
Population	0.78	1.02	0.56
Per capita income	1.90	2.80	0.73
Biofuels	3.88	4.72	3.04
Total factor productivity			
Crops	0.94	1.14	0.50
Livestock	2.11	2.49	0.78
Processed foods	0.89	1.05	0.33
Parameters	Mode	Max	Min
Demand elasticities			
Future price elasticities			
Crops	−0.10	−0.02	−0.31
Livestock	−0.34	−0.29	−0.5
Processed foods	−0.38	−0.29	−0.65
Future income elasticities			
Crops	−0.06	0.26	−0.17
Livestock	0.2	0.49	0.1
Processed foods	0.21	0.55	0.1
Land supply response	0.28	0.56	0.11
Non-land supply response	1.34	2.68	0.49
Elasticity of substitution: crop	3	4.5	0.24
Elasticity of substitution: livestock	1.16	1.51	0.81
Elasticity of transformation: Local and global markets	3	3.9	2.1

Notes: For each driver and parameter, we postulate a global triangular distribution using scalars to convert some of these global shocks to regional values (Appendix Table A3).
Population and per capita incomes: SSP Projections Database v0.5 (O'Neill et al. 2014; Kriegler et al. 2012) for population and per capita income growth rates. The modal values are based on SSP2 projections which are built on the assumption that current trends continue. We construct the max and min growth rates for population using SSP3 and SSP1, and SSP5 and SSP3 for income growth, respectively. Note that these SSP combinations encompass the full range of expected global population and income growth in the SSP database.
*Biofuels:*The max and min for global biofuel growth is taken from IEA (2014) *New Policies* scenario 2012-40 p.a. rate and *Current Policies* scenario 2030-40 p.a. rate while the mode calibrated to *Current Policies* scenario 2012-40 p.a. rate. Under the IEA scenarios, *Current* policies reflect projections given governmental energy and emissions policies enacted as of mid-2014 while *New* policies build on this projection albeit with cautious implementation of future policies that have not been fully developed at the moment (IEA 2014).
Total Factor Productivity: Productivity growth is based on TFP estimates. For the crop and livestock sectors, we rely on projections by Ludena et al. (2007) which assumes eventual convergence of productivity growth across regions. Max and min TFP growth rates are based the periods: 2001-20 (the two decades of most rapid projected global growth) and 1961-80 (the slowest historical TFP decades) while modes are based on 2001–2040 rates. Lacking data for processed foods TFP growth, we impose the normalized range of livestock TFP growth using estimate from Griffith et al. (2004) as the mode.
Demand Elasticities: Max and min values of future global average demand elasticities reported in the table are based on the full range of predicted regional demand elasticities in SIMPLE at base year 2006. Note that demand elasticities in SIMPLE are calculated from OLS regressions linking the natural log of adjusted per capita incomes to country-level demand elasticities computed by Muhammad et al. (2011) in order to capture the declining responsiveness of consumers to food price change and increased food spending on livestock and processed foods at higher income levels.
Supply and Substitution Elasticities: The range of global land supply response is based on the 5-year and 45-year own-price elasticities of U. S. cropland from Ahmed et al. (2008) which incorporates information on the response of land to economic markets as well as the natural transition of land across uses overtime. Lacking data, we impose the same range for the global non-land supply response albeit normalized to modal value. The max and min values of input substitution elasticities for crops are calibrated using the range of estimates of U.S. corn yield price response assembled by Keeney and Hertel (2009) as a guide. Finally, we do not have sufficient data to compute for the ranges of the input elasticity of substitution in the livestock sector and the elasticity of transformation between local and global markets. For these parameters, we simply assume that the max and min values are ±30% of modal values.

Table A3
Regional scalars for selected parameters and shocks.

Regions	Land supply response	Population	Per capita income	TFP: livestock	TFP: crop
Eastern Europe	2.00	−0.32	1.99	0.38	1.39
North Africa	0.39	1.28	2.01	0.14	1.30
Sub Saharan Africa	2.00	4.02	3.62	0.14	0.12
South America	2.00	0.89	1.61	1.21	1.26
Australia/New Zealand	2.00	1.02	0.57	0.14	0.36
European Union+	0.39	0.03	0.49	0.14	0.52
South Asia	1.00	1.18	6.36	0.74	0.74
Central America	1.00	1.17	1.20	1.21	0.74
Southern Africa	1.00	0.49	2.00	0.14	0.97
Southeast Asia	1.00	0.92	3.34	1.21	1.28
Canada/US	1.00	0.72	0.42	0.14	0.92
China/ Mongolia	1.00	−0.12	6.54	1.21	1.17
Middle East	0.39	1.93	0.86	0.14	0.47
Japan/Korea	0.39	−0.35	0.77	0.14	1.00
Central Asia	2.00	1.46	4.12	0.38	1.39

Notes: Regional scalars allow us to preserve regional variations in model parameters and/or shocks during each of our Monte Carlo simulations (see model shock and parameter distributions in Appendix Table A2). For example, we know that the regional scalar for population growth for South Asia is 1.18. This means that relative to the global population, South Asia's regional growth rate will always be 18% higher than the global growth rate. If global growth rate is 10% (20%) then South Asia's regional growth rate is around 11.8% (23.6%). For the land supply response, the scalars are calculated relative to the regional value for the North America region. Scalars for population and per capita income are calculated relative to the global growth rate based on SSP2 projections. For livestock and crop TFP, scalars are constructed from regional and global rates from Ludena et al. (2007) and Fuglie (2012), respectively.

References

Philip, Abbott, Chris Hurt, Wallace E. Tyner. 2011. "What's Driving Food Prices in 2011?" Issue Report, Farm Foundation.

Ahmed, Syud Amer, Hertel, Thomas, Lubowski, Ruben. 2008. Calibration of a Land Cover Supply Function Using Transition Probabilities. GTAP Research Memorandum 14. West Lafayette, Indiana, USA: Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University. 〈http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2947〉.

Alston, Julian M., Beddow, Jason M., Pardey, Philip G., 2009. Agricultural research, productivity, and food prices in the long run. Science 325 (5945), 1209–1210. http://dx.doi.org/10.1126/science.1170451.

Alston, Julian M., Beddow, Jason M., Pardey, Philip G., 2010. Global patterns of crop yields and other partial productivity measures and prices. In: The Shifting Patterns of Agricultural Productivity Worldwide, Center for Agricultural and Rural Development, Ames, Iowa: CARD-MATRIC Electronic Book, pp. 39–61.

Babcock, Bruce A., 2013. Ethanol without subsidies: an oxymoron or the new reality? Am. J. Agric. Econ. . http://dx.doi.org/10.1093/ajae/aat036, June, aat036

Baldos, Uris, Lantz, C., Hertel, Thomas W., 2013. Looking back to move forward on model validation: insights from a global model of agricultural land use. Environ. Res. Lett. 8 (3), 034024. http://dx.doi.org/10.1088/1748–9326/8/3/034024.

Baldos, Uris, Lantz, C., Hertel, Thomas W., 2014. Global food security in 2050: the role of agricultural productivity and climate change. Aust. J. Agric. Resour. Econ. . http://dx.doi.org/10.1111/1467–8489.12048

Baldos, Uris, Lantz, C., Hertel, Thomas W., 2015. The role of international trade in managing food security risks from climate change. Food Secur. 7 (2), 275–290. http://dx.doi.org/10.1007/s12571-015-0435-z.

Beintema, Nienke, Stads, Gert-Jan, Fuglie, Keith, Heisey, Paul, 2012. ASTI Global Assessment of Agricultural R&D Spending: Developing Countries Accelerate Investment. International Food Policy Report, International Food Policy Research Institute, Agricultural Science and Technology Indicators, Global Forum on Agricultural Research, Washington D.C., USA.

Bloom, David E., 2011. 7 billion and counting. Science 333 (6042), 562–569. http://dx.doi.org/10.1126/science.1209290.

Burke, Jacob, Villholth, Karen, 2007. Groundwater: a global assessment of scale and significance.. In: Molden, David (Ed.), Water for Food, Water for Life. Earthscan and International Water Management Institute, London and Colombo, pp. 395–423.

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

Cranfield, John A., Preckel, Paul V., Eales, James S., Hertel, Thomas W., 2002. Estimating consumer demands across the development spectrum: maximum likelihood estimates of an implicit direct additivity model. J. Dev. Econ. 68 (2), 289–307, doi:16/S0304-3878(02)00014-7.

Döll, P., Fiedler, K., 2007. Global-scale modeling of groundwater recharge. Hydrol. Earth Syst. Sci. Discuss. 4 (6), 4069–4124.

European Commission. 2012. Executive summary of the impact assessment on indirect land-use change related to biofuels and bioliquids, Commission Staff Working Document, Brussels, Belgium.

Evans, L.T., 1993. Crop Evolution, Adaptation and Yield. Cambridge University Press, New York, NY, USA.

Ezeh, Alex C., Bongaarts, John, Mberu, Blessing, 2012. Global population trends and policy options. Lancet 380 (9837), 142–148. http://dx.doi.org/10.1016/S0140-6736(12)60696-5.

FAO, 2014. FAOSTAT, September 2014 25. 〈http://faostat.fao.org/〉.

FAO Statistical Database, 2011. Food and Agriculture Organisation of the UN, Rome, Italy. 〈http://faostat.fao.org/〉.

Federal Reserve Bank of Minneapolis, 2014. Consumer Price Index and Inflation Rates (Estimate), 1800. 〈http://www.minneapolisfed.org/community_education/teacher/calc/hist1800.cfm〉.

Fischer, Anthony, Byerlee, Derek, Edmeades, Greg, 2014. Crop Yields and Global Food Security: Will Yield Increase Conitinue to Feed the World?. ACIAR, Canberra, Australia.

Fischer, Günther, Hizsnyik, Eva, Prieler, Sylvia, Shah, Mahendra, van Velthuizen, Harrij, 2009. Biofuels and Food Security: Implications of an Accelerated Biofuels Production. Organization of the Petroleum Exporting Countries Fund for International Development, Vienna, Austria.

Foley, Jonathan A., Ramankutty, Navin, Brauman, Kate A., Cassidy, Emily S., Gerber, James S., Johnston, Matt, Mueller, Nathaniel D., et al., 2011. Solutions for a cultivated planet. Nature 478 (7369), 337–342. http://dx.doi.org/10.1038/nature10452.

Food and Agriculture Organization of the UN Media Centre, 2013. Feeding Nine Billion in 2050, April 12. 〈http://www.fao.org/news/story/en/item/174172/icode/〉.

Fouré, Jean, Bénassy-Quéré, Agnès, Fontagné, Lionel, 2013. Modelling the world economy at the 2050 horizon. Econ. Transit. 21 (4), 617–654. http://dx.doi.org/10.1111/ecot.12023.

Fuglie, 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.

Griffith, Rachel, Redding, Stephen, Van Reenen, John, 2004. Mapping the two faces of R&D: productivity growth in a panel of OECD industries. Rev. Econ. Stat. 86 (4), 883–895. http://dx.doi.org/10.1162/0034653043125194.

Harrison, W. Jill, Horridge, J. Mark, Pearson, K.R., 2000. Decomposing simulation results with respect to exogenous shocks. Comput. Econ. 15 (3), 227–249.

Headey, Derek, 2010. Rethinking the global food crisis: the role of trade shocks. Discussion Paper 958, International Food Policy Research Institute, Washington D.C., USA.

Headey, Derek, Fan, Shenggen, 2008. Anatomy of a crisis: the causes and consequences of surging food prices. Agric. Econ. 39, 375–391. http://dx.doi.org/10.1111/j.1574–0862.2008.00345.x.

Headey, Derek, Fan, Shenggen, 2010. Reflections on the Global Food Crisis : How Did It Happen? How Has It Hurt? And How Can We Prevent the next One? Research Monograph 105. International Food Policy Research Institute, Washington D.C., USA.

Herdt, Robert W., 1979. An Overview of the Constraints Project Results. In: Farm-Level Constraints to High Rice Yields in Asia: 1974–1977, International Rice Research Institute, Los Baños, Laguna, Philippines, pp. 395–421.

Hertel, Thomas W., Ramankutty, N., Baldos, Uris Lantz C., 2014. Global market integration increases likelihood that a future african green revolution could increase crop land use and CO_2 emissions. Proc. Natl. Acad. Sci. 111 (38), 13799–13804. http://dx.doi.org/10.1073/pnas.1403543111.

Hertel, T.W., Baldos, U.L.C., 2016. Predicting long term food demand, cropland use and prices. Annu. Rev. Resour. Econ. (forthcoming)

IEA, World Energy Outlook, 2008. OECD Publishing 〈http://www.oecd-ilibrary.org/content/book/weo-2008-en〉.

IEA, World Energy Outlook, 2012. OECD Publishing 〈http://www.oecd-ilibrary.org/content/book/weo-2012-en〉.

IEA, 2014. World Energy Outlook. OECD Publishing 〈http://www.oecd-ilibrary.org/content/book/weo-2008-en〉.

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 University Press, Cambridge, United Kingdom and New York, NY, USA.

Junker, Franziska, Wolf, Verena, Marquardt, Sandra, Ledebur, Oliver, 2015. Changes to EU Biofuel Policy – Turmoil on Feedstock Markets?, Milan, Italy.

Keeney, Roman, Hertel, T.W., 2009. Indirect land use impacts of US biofuels policies: the importance of acreage, yield and bilateral trade responses. Am. J. Agric. Econ. 91, 895–909.

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. Chang. 22 (4), 807–822. http://dx.doi.org/10.1016/j.gloenvcha.2012.05.005.

Liu, Jing, Hertel, Thomas W., Taheripour, Farzad, Zhu, Tingju, Ringler, Claudia, 2014. International trade buffers the impact of future irrigaiton shortfalls. Glob. Environ. Chang. (In Press)

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

Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science 333 (May), 616–620. http://dx.doi.org/10.1126/science.1204531.

Long, S.P., 1991. Modification of the response of photosynthetic productivity to rising temperature by atmospheric co2 concentrations: has its importance been underestimated? Plant Cell Environ. 14 (8), 729–739.

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. http://dx.doi.org/10.1111/j.1574–0862.2007.00218.x.

McGrath, Justin M., Lobell, David B., 2013. Regional disparities in the CO_2 fertilization effect and implications for crop yields. Environ. Res. Lett. 8 (1), 014054. http://dx.doi.org/10.1088/1748–9326/8/1/014054.

McKinsey & Co, 2009. Charting Our Water Future: Economic Frameworks to Inform Decision-Making. 2030 Water Resources Group, McKinsey & Co.

Miranowski, John, Rosburg, Alicia, 2013. Long-term biofuel projections under different oil price scenarios. AgBioForum 15 (4), 1–9.

Mitchell, D., 2008. A note on rising food prices. Policy Research Working Paper 4682, World Bank, Development Prospects Group, Washington DC, USA.

Msangi, Siwa, Ewing, Mandy, Rosegrant, Mark, 2010. Biofuels and agricultural growth: challenges for developing agricultural economies and opportunities for investment. In: Handbook of Bioenergy Economics and Policy, Springer, The Netherlands, pp. 73–90. doi:http://dx.doi.org/10.1007/978-1-4419-0369-3_6.

Mueller, Nathaniel D., Gerber, James S., Johnston, Matt, Ray, Deepak K., Ramankutty, Navin, Foley, Jonathan A., 2012. Closing yield gaps through nutrient and water management. Nature 490 (7419), 254–257. http://dx.doi.org/10.1038/nature11420.

Andrew, Muhammad, Seale, James L. Jr., Birgit, Meade, 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/〉.

National Research Council, 2011. Renewable fuel standard: potential economic effects of U.S. biofuel policy, National Academy of Sciences.

Gerald, Nelson, Rosegrant, Mark W., Palazzo, Amanda, Gray, Ian, Ingersoll, Christina, Robertson, Richard D., Tokgoz, Simla, et al., 2010. Food security, farming, and climate change to 2050: scenarios, results, policy options. Research reports, Gerald, C., Nelson, et al., International Food Policy Research Institute (IFPRI). 〈http://econpapers.repec.org/paper/fprresrep/geraldnelson.htm〉.

OECD/FAO, 2013. OECD-FAO Agricultural Outlook 2013–2022. OECD-FAO Agricultural Outlook, OECD/FAO. http://dx.doi.org/10.1787/agr_outlook-2013-en.

OECD-FAO, 2015. OECD-FAO Agricultural Outlook 2015, Agricultural Outlook, Paris and Rome, OECD/FAO 〈http://www.fao.org/3/a-i4738e.pdf〉.

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

Oxfam, 2012. Extreme weather, extreme prices: the costs of feeding a warming world, Oxfam Issue Briefing, Oxfam International.

Paarlberg, Don, 1981. "Enough Food? Sure, If We Don't Play It Dumb.. In: Hayes, Jack (Ed.), Will There Be Enough Food?: The 1981 Yearbook of Agriculture. USA: US Department of Agriculture, Washington DC, pp. 282–294.

Paltsev, Sergey, 2012. Implications of Alternative Mitigation Policies on World Prices for Fossil Fuels and Agricultural Products. Working Paper 2012/65. WIDER Working Paper, UNU-WIDER, Helsinki, Finland.

Pardey, Philip G., Beintema, Nienke M., Dehmer, Steven, Wood, Stanley, 2006. Agricultural Research: A Growing Global Divide?. International Food Policy Research Institute (IFPRI) 〈http://ideas.repec.org/p/fpr/fprepo/17.html〉.

Pearson, Ken, Hertel, Thomas, Horridge, Mark, 2000. AnalyseGE: software assisting modellers in the analysis of their results. In Practical Aspects of GE Modelling, Melborne, Australia.

Piesse, Jenifer, Thirtle, Colin, 2009. Three bubbles and a panic: an explanatory review of recent food commodity price events. Food Policy 34 (2), 119–129. http://dx.doi.org/10.1016/j.foodpol.2009.01.001.

Pingali, Prabhu, 2007. Westernization of asian diets and the transformation of food systems: implications for research and policy. Food Policy 32 (3), 281–298. http://dx.doi.org/10.1016/j.foodpol.2006.08.001.

Rosegrant, Mark W., Cai, Ximing, Cline, Sarah A., 2002. World Water and Food to 2025 : Dealing with Scarcity. International Food Policy Research Institute, Washington, DC, USA.

Rosegrant, Mark W., Koo, Jawoo, Cenacchi, Nicola, Ringler, Claudia, Robertson, Richard, Fisher, Myles, Cox, Cindy, Garrett, Karen, Perez, Nicostrato D., 2014. Food Security in a World of Natural Resource Scarcity : The Role of Agricultural Technologies. International Food Policy Research Institute, Washington D.C., USA.

Rosegrant, Mark W., Ringler, Claudia, Zhu, Tingju, Tokgoz, Simla, Bhandary, Prapti, 2013. Water and food in the bioeconomy: challenges and opportunities for development. Agric. Econ., 1–12. http://dx.doi.org/10.1111/agec.12058.

Rosenzweig, Cynthia, Elliott, Joshua, Deryng, Delphine, Ruane, Alex C., Müller, Christoph, Arneth, Almut, Boote, Kenneth J., et al., 2013. Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. Proc. Natl. Acad. Sci. . http://dx.doi.org/10.1073/pnas.1222463110

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. http://dx.doi.org/10.1016/j.eneco.2011.06.004.

Schlenker, Wolfram, Lobell, David B., 2010. Robust negative impacts of climate change on african agriculture. Environ. Res. Lett. 5 (1), 014010. http://dx.doi.org/10.1088/1748–9326/5/1/014010.

Schlenker, Wolfram, Roberts, Michael J., 2009. Nonlinear temperature effects indicate severe damages to u.s. crop yields under climate change. Proc. Natl. Acad. Sci. 106 (37), 15594–15598. http://dx.doi.org/10.1073/pnas.0906865106.

Searchinger, Timothy, Ralph Heimlich, R.A., Houghton, Fengxia, Dong, Amani, Elobeid, Jacinto, Fabiosa, Simla, Tokgoz, Dermot Hayes, Yu, Tun-Hsiang, 2008. Use of U.S. croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319 (5867), 1238–1240. http://dx.doi.org/10.1126/science.1151861.

Steinbuks, Jevgenijs, Hertel, Thomas W., 2013. Energy prices will play an important role in determining global land use in the twenty first century. Environ. Res. Lett. 8 (1) ⟨http://stacks.iop.org/1748–9326/8/i=1/a=014014⟩.

Timmer, C. peter, 2010. Reflections on food crises past. Food Policy 35 (1), 1–11. http://dx.doi.org/10.1016/j.foodpol.2009.09.002.

Tubiello, Francesco N., Soussana, Jean-François, Howden, S. Mark, 2007. Crop and pasture response to climate change. Proc. Natl. Acad. Sci. 104 (50), 19686–19690. http://dx.doi.org/10.1073/pnas.0701728104.

Tyner, Wallace E., 2008. The US ethanol and biofuels boom: its origins, current status, and future prospects. BioScience 58 (7), 646–653. http://dx.doi.org/10.1641/B580718.

UN Population Division, 2000. World at Six Billion.

UN Population Division, 2013. "World Population Prospects: The 2012 Revision." Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, New York, USA, ⟨http://esa.un.org/unpd/wpp/index.htm⟩.

US Department of Agriculture Economic Research Service, 2014. Feed Grains Database. ⟨http://www.ers.usda.gov/data-products/feed-grains-database/⟩.

U.S. Energy Information Administration, 2013. Annual energy outlook 2013: with projections to 2040, Annual Energy Outlook DOE/EIA-0383, U.S. Department of Energy, Washington, DC, USA.

US EPA, 2015. Regulations & standards: fuels and fuels addtives. Policies & Guidance. (accessed September 11). ⟨http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm⟩.

Westhoff, Patrick, 2010. The Economics of Food. Financial Times Press, New Jersey, USA.

World Bank, 2013. Food Crisis, April 15. ⟨http://www.worldbank.org/foodcrisis/bankinitiatives.htm⟩.

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

World Development Indicators, 2013. Washington, D.C., USA: World Bank. ⟨http://data.worldbank.org/data-catalog/world-development-indicators⟩.