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

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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 percent 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.

Keywords: Long run crop prices, food demand and supply, agricultural productivity, population growth, income growth, biofuels

47 **1. Introduction**

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

60 Nonetheless, there remains a strong belief that the future holds higher crop prices in store
 61 – particularly once climate change impacts and policies are factored into the analysis. Oxfam
 62 (2012) reported that “...the average price of staple foods... could more than double in the next 20
 63 years compared with 2010 trend prices” in the wake of climate change. The International Food
 64 Policy Research Institute projected that the rise in the price of food grains such as rice, maize and
 65 wheat from 2010 to 2050 might be as high as 92% to 64% under current agricultural
 66 technologies (M. W. Rosegrant et al. 2014). A recent MIT study (Paltsev 2012) suggests that
 67 global agricultural prices from 2010 to 2050 may increase by more than 20%-30% if GHG
 68 mitigation policies are implemented. The idea that future commodity prices will rise continues to
 69 be pervasive in the public discourse.

70 *We believe that the high price ‘consensus’ has been misguided.* Observers were overly
 71 influenced by the 2007/08 and 2010/11 spikes in commodity prices, which, we believe, were
 72 largely driven by transitory phenomena, including record low stocks, an exceptional build-up in
 73 the U.S. and European Union biofuels programs, reactionary market interventions, and a
 74 succession of adverse weather events (Abbott, Hurt, and Tyner 2011; Piesse and Thirtle 2009;
 75 Headey 2010; Headey and Fan 2010; Headey and Fan 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 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. Figure 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 1970's, food supply and trade shocks drove real food prices to levels not seen since the 1940's. 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 1970's? 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 and Hertel 2013).

The key elements of SIMPLE are laid out in Figure 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 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 and Hertel 2013) and the model has been used in studies focusing on climate change mitigation and adaptation (Lobell, Baldos, and Hertel 2013), long run food security analysis (Baldos and Hertel 2014) assessing the impact of green revolutions on land use and food security (Hertel, Ramankutty, and Baldos 2014), and for assessment of the interplay between climate change impacts and global trade (Baldos and Hertel 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 to 2006) to examine how well the SIMPLE model reproduces the decline in global crop prices over this historical 45-year period (see also Baldos and Hertel (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 (2014). 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 & 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 and Hertel 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.

An important feature of SIMPLE is that it allows for a decomposition² 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

¹ These are based on aggregate global changes using data from FAOSTAT (2014) between 1961 to 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, Hertel, and Horridge 2000) which has many useful features for purposes of analysis. One of these is the subtotals feature developed by Harrison, Horridge and Pearson (2000) which utilizes numerical integration techniques in order to exactly partition the impacts of different exogenous shocks on endogenous variables of interest.

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, Davis, and Lobell 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 (A. Fischer, Byerlee, and Edmeades 2014)

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; Ezech, Bongaarts, and Mberu 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. 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 1980's 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 1. 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 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 Figure 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, Bénassy-Quéré, and Fontagné 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 Figure A2).

The second bar in Figure 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 and Hertel 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 2004-2007 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, Hurt, and Tyner 2011) and many studies suggest that biofuels will place significant pressures on future crop demand and prices (G. Fischer et al. 2009; Msangi, Ewing, and Rosegrant 2010; Piesse and Thirtle 2009; Headey and Fan 2010; Headey and Fan 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 Figure 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.

4. 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, Beddow, and Pardey 2009; Alston, Beddow, and Pardey 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 1980-2005, 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 1990’s (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 noted 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, Soussana, and Howden 2007). Between the two, temperature changes transmit the strongest signal in the context of agricultural impacts (Lobell, Schlenker, and Costa-Roberts 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, Schlenker, and Costa-Roberts 2011).

Another aspect of climate change which could significantly affect agricultural productivity and global food availability is the presence of heightened CO₂ concentrations in the atmosphere. This can directly benefit crop yields through increases in leaf CO₂ levels and reductions in stomatal conductance, thereby boosting the optimum temperature for C3 crops (Long 1991). However, these CO₂ impacts differ widely across crop types as well as agro-climatic conditions. And capitalizing on the elevated CO₂ 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 CO₂ 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 CO₂ 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, Cai, & Cline, 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, Byerlee and Edmeades (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 (A. Fischer, Byerlee, and Edmeades 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 Figure 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 (Figure 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.

5. 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 Figure 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 (Figure 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, Baldos, and van der Mensbrugghe 2016). The final bar in Figure 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 Figure 1, *in the long run, crop prices are most likely to resume a downward trend, albeit slower than in the historical period.*

6. Conclusions

In order to understand the future, it is important to study history, and the food crisis of the 1970’s 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 1970’s 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

469 and agricultural productivity – the main historical drivers of food demand and supply. With high
470 population growth and a stagnation of TFP growth in the crops sector, food prices will indeed
471 rise in the future. In contrast, slower population growth and faster crop TFP growth will result in
472 even lower food prices, declining as fast as that observed reduction from 1961 to 2006. Our
473 Monte Carlo analysis in which both model parameters and long run drivers are systematically
474 varied reveals that two-thirds of the possible future outcomes show declining food prices
475 between 2006 and 2051. Thus, we conclude that current expectations of rising long run food
476 prices are misplaced and are likely motivated by extreme assumptions regarding the future trends
477 in key drivers of global agriculture.

478

479 **REFERENCES**

480

- 481 Abbott, Philip, Chris Hurt, and Wallace E. Tyner. 2011. "What's Driving Food Prices in 2011?"
482 Issue Report. Farm Foundation.
- 483 Ahmed, Syud Amer, Thomas Hertel, and Ruben Lubowski. 2008. "Calibration of a Land Cover
484 Supply Function Using Transition Probabilities." GTAP Research Memorandum 14.
485 West Lafayette, Indiana, USA: Center for Global Trade Analysis, Department of
486 Agricultural Economics, Purdue University.
487 http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2947.
- 488 Alston, Julian M., Jason M. Beddow, and Philip G. Pardey. 2009. "Agricultural Research,
489 Productivity, and Food Prices in the Long Run." *Science* 325 (5945): 1209–10.
490 doi:10.1126/science.1170451.
- 491 ———. 2010. "Global Patterns of Crop Yields and Other Partial Productivity Measures and
492 Prices." In *The Shifting Patterns of Agricultural Productivity Worldwide*, 39–61. Center
493 for Agricultural and Rural Development, Ames, Iowa: CARD-MATRIC Electronic Book.
- 494 Babcock, Bruce A. 2013. "Ethanol without Subsidies: An Oxymoron or the New Reality?"
495 *American Journal of Agricultural Economics*, June, aat036. doi:10.1093/ajae/aat036.
- 496 Baldos, Uris Lantz C., and Thomas W. Hertel. 2013. "Looking back to Move Forward on Model
497 Validation: Insights from a Global Model of Agricultural Land Use." *Environmental*
498 *Research Letters* 8 (3): 034024. doi:10.1088/1748-9326/8/3/034024.
- 499 ———. 2014. "Global Food Security in 2050: The Role of Agricultural Productivity and
500 Climate Change." *Australian Journal of Agricultural and Resource Economics*.
501 doi:10.1111/1467-8489.12048.
- 502 ———. 2015. "The Role of International Trade in Managing Food Security Risks from Climate
503 Change." *Food Security* 7 (2): 275–90. doi:10.1007/s12571-015-0435-z.
- 504 Beintema, Nienke, Gert-Jan Stads, Keith Fuglie, and Paul Heisey. 2012. "ASTI Global
505 Assessment of Agricultural R&D Spending: Developing Countries Accelerate
506 Investment." International Food Policy Report. Washington D.C., USA: International
507 Food Policy Research Institute, Agricultural Science and Technology Indicators, Global
508 Forum on Agricultural Research.
- 509 Bloom, David E. 2011. "7 Billion and Counting." *Science* 333 (6042): 562–69.
510 doi:10.1126/science.1209290.
- 511 Burke, Jacob, and Karen Villholth. 2007. "Groundwater: A Global Assessment of Scale and
512 Significance." In *Water for Food, Water for Life*, edited by David Molden, 395–423.
513 London and Colombo: Earthscan and International Water Management Institute.
- 514 Burney, Jennifer A., Steven J. Davis, and David B. Lobell. 2010. "Greenhouse Gas Mitigation by
515 Agricultural Intensification." *Proceedings of the National Academy of Sciences* 107 (26):
516 12052–57. doi:10.1073/pnas.0914216107.
- 517 Cranfield, John A., Paul V. Preckel, James S. Eales, and Thomas W. Hertel. 2002. "Estimating
518 Consumer Demands across the Development Spectrum: Maximum Likelihood Estimates
519 of an Implicit Direct Additivity Model." *Journal of Development Economics* 68 (2): 289–
520 307. doi:10.1016/S0304-3878(02)00014-7.

- Döll, P., and K. Fiedler. 2007. "Global-scale modeling of groundwater recharge." *Hydrology and Earth System Sciences Discussions Discussions* 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*. New York, NY, USA: Cambridge University Press.
- Ezeh, Alex C, John Bongaarts, and Blessing Mberu. 2012. "Global Population Trends and Policy Options." *The Lancet* 380 (9837): 142–48. doi:10.1016/S0140-6736(12)60696-5.
- FAO. 2014. "FAOSTAT." September 25. <http://faostat.fao.org/>.
- "FAO Statistical Database." 2011. Rome, Italy: Food and Agriculture Organisation of the UN. <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, Derek Byerlee, and Greg edmeades. 2104. *Crop Yields and Global Food Security: Will Yield Increase Conitinue to Feed the World?* Canberra, Australia: ACIAR.
- Fischer, Günther, Eva Hizsnyik, Sylvia Prieler, Mahendra Shah, and Harrij van Velthuisen. 2009. "Biofuels and Food Security: Implications of an Accelerated Biofuels Production." Issue 38. Pamphlet Series. Vienna, Austria: Organization of the Petroleum Exporting Countries Fund for International Development.
- Foley, Jonathan A., Navin Ramankutty, Kate A. Brauman, Emily S. Cassidy, James S. Gerber, Matt Johnston, Nathaniel D. Mueller, et al. 2011. "Solutions for a Cultivated Planet." *Nature* 478 (7369): 337–42. doi: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, Agnès Bénassy-Quéré, and Lionel Fontagné. 2013. "Modelling the World Economy at the 2050 Horizon." *Economics of Transition* 21 (4): 617–54. doi:10.1111/ecot.12023.
- Fuglie, Keith O. 2012. "Productivity Growth and Technology Capital in the Global Agricultural Economy." In *Productivity Growth In Agriculture: An International Perspective*, edited by Keith O. Fuglie, Sun Ling Wang, and V Eldon Ball, 335–68. Cambridge, MA, USA: CAB International.
- Griffith, Rachel, Stephen Redding, and John Van Reenen. 2004. "Mapping the Two Faces of R&D: Productivity Growth in a Panel of OECD Industries." *Review of Economics and Statistics* 86 (4): 883–95. doi:10.1162/0034653043125194.
- Harrison, W. Jill, J. Mark Horridge, and K.R. Pearson. 2000. "Decomposing Simulation Results with Respect to Exogenous Shocks." *Computational Economics*, Computational Economics, 15 (3): 227–49.
- Headey, Derek. 2010. "Rethinking the Global Food Crisis: The Role of Trade Shocks." Discussion Paper 958. Washington D.C., USA: International Food Policy Research Institute.
- Headey, Derek, and Shenggen Fan. 2008. "Anatomy of a Crisis: The Causes and Consequences of Surging Food Prices." *Agricultural Economics* 39: 375–91. doi:10.1111/j.1574-0862.2008.00345.x.

- . 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. Washington D.C., USA: International Food Policy Research Institute.
- Herd, Robert W. 1979. “An Overview of the Constraints Project Results.” In *Farm-Level Constraints to High Rice Yields in Asia: 1974–1977*, 395–421. Los Baños, Laguna, Philippines: International Rice Research Institute.
- Hertel, Thomas W., N. Ramankutty, and Uris Lantz C. Baldos. 2014. “Global Market Integration Increases Likelihood That a Future African Green Revolution Could Increase Crop Land Use and CO2 Emissions.” *Proceedings of the National Academy of Sciences* 111 (38): 13799–804. doi:10.1073/pnas.1403543111.
- Hertel, T. W., U. L. C. Baldos, and van der Mensbrugghe. 2016. “Predicting Long Term Food Demand, Cropland Use and Prices.” *Annual Review of Resource Economics* forthcoming.
- 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, United Kingdom and New York, NY, USA: Cambridge University Press.
- Junker, Franziska, Verena Wolf, Sandra Marquardt, and Oliver Ledebur. 2015. “Changes to EU Biofuel Policy - Turmoil on Feedstock Markets?” In . Milan, Italy.
- Keeney, Roman, and T. W. Hertel. 2009. “Indirect Land Use Impacts of US Biofuels Policies: The Importance of Acreage, Yield and Bilateral Trade Responses.” *American Journal of Agricultural Economics* 91: 895–909.
- Kriegler, Elmar, Brian C. O’Neill, Stephane Hallegatte, Tom Kram, Robert J. Lempert, Richard H. Moss, and Thomas Wilbanks. 2012. “The Need for and Use of Socio-Economic Scenarios for Climate Change Analysis: A New Approach Based on Shared Socio-Economic Pathways.” *Global Environmental Change* 22 (4): 807–22. doi:10.1016/j.gloenvcha.2012.05.005.
- Liu, Jing, Thomas Hertel, Farzad Taheripour, Tingju Zhu, and Claudia Ringler. 2014. “International Trade Buffers the Impact of Future Irrigation Shortfalls.” *Global Environmental Change* In Press.
- Lobell, D. B., Uris Lantz C. Baldos, and Thomas W. Hertel. 2013. “Climate Adaptation as Mitigation: The Case of Agricultural Investments.” *Environmental Research Letters* 8. doi:10.1088/1748-9326/8/1/015012.
- Lobell, D. B., W. Schlenker, and J. Costa-Roberts. 2011. “Climate Trends and Global Crop Production Since 1980.” *Science* 333 (May): 616–20. doi:10.1126/science.1204531.
- Long, SP. 1991. “Modification of the Response of Photosynthetic Productivity to Rising Temperature by Atmospheric CO2 Concentrations: Has Its Importance Been Underestimated?” *Plant, Cell & Environment* 14 (8): 729–39.
- Ludena, Carlos E., Thomas W. Hertel, Paul V. Preckel, Kenneth Foster, and Alejandro Nin. 2007. “Productivity Growth and Convergence in Crop, Ruminant, and Nonruminant Production: Measurement and Forecasts.” *Agricultural Economics* 37 (1): 1–17. doi:10.1111/j.1574-0862.2007.00218.x.
- McGrath, Justin M., and David B. Lobell. 2013. “Regional Disparities in the CO2 Fertilization Effect and Implications for Crop Yields.” *Environmental Research Letters* 8 (1): 014054. doi: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, and Alicia Rosburg. 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. Washington DC, USA: World Bank, Development Prospects Group.
- Msangi, Siwa, Mandy Ewing, and Mark Rosegrant. 2010. "Biofuels and Agricultural Growth: Challenges for Developing Agricultural Economies and Opportunities for Investment." In *Handbook of Bioenergy Economics and Policy*, 73–90. The Netherlands: Springer. http://dx.doi.org/10.1007/978-1-4419-0369-3_6.
- Mueller, Nathaniel D., James S. Gerber, Matt Johnston, Deepak K. Ray, Navin Ramankutty, and Jonathan A. Foley. 2012. "Closing Yield Gaps through Nutrient and Water Management." *Nature* 490 (7419): 254–57. doi:10.1038/nature11420.
- Muhammad, Andrew, James L. Seale Jr., Birgit Meade, and Anita Regmi. 2011. "International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data." Technical Bulletin TB-1929. Washington, D.C., USA: Economic Research Service, US Department of Agriculture. <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.
- Nelson, Gerald, Mark W. Rosegrant, Amanda Palazzo, Ian Gray, Christina Ingersoll, Richard D. Robertson, Simla Tokgoz, 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., Elmar Kriegler, Keywan Riahi, Kristie L. Ebi, Stephane Hallegatte, Timothy R. Carter, Ritu Mathur, and Detlef P. van Vuuren. 2014. "A New Scenario Framework for Climate Change Research: The Concept of Shared Socioeconomic Pathways." *Climatic Change* 122 (3): 387–400. doi:10.1007/s10584-013-0905-2.
- 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 *Will There Be Enough Food?: The 1981 Yearbook of Agriculture*, edited by Jack Hayes, pp 282–94. Washington DC, USA: US Department of Agriculture.
- Paltsev, Sergey. 2012. "Implications of Alternative Mitigation Policies on World Prices for Fossil Fuels and Agricultural Products." Working Paper 2012/65. WIDER Working Paper. Helsinki, Finland: UNU-WIDER.
- Pardey, Philip G., Nienke M. Beintema, Steven Dehmer, and Stanley Wood. 2006. "Agricultural Research: A Growing Global Divide?" International Food Policy Research Institute (IFPRI). <http://ideas.repec.org/p/fpr/fprepo/17.html>.

- Pearson, Ken, Thomas Hertel, and Mark Horridge. 2000. "AnalyseGE: Software Assisting Modellers in the Analysis of Their Results." In *Practical Aspects of GE Modelling*. Melbourne, Australia.
- Piesse, Jenifer, and Colin Thirtle. 2009. "Three Bubbles and a Panic: An Explanatory Review of Recent Food Commodity Price Events." *Food Policy* 34 (2): 119–29. doi: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): 281–98. doi:10.1016/j.foodpol.2006.08.001.
- Rosegrant, Mark W., Ximing Cai, and Sarah A. Cline. 2002. "World Water and Food to 2025 : Dealing with Scarcity." Washington, DC, USA: International Food Policy Research Institute.
- Rosegrant, Mark W., Jawoo Koo, Nicola Cenacchi, Claudia Ringler, Richard Robertson, Myles Fisher, Cindy Cox, Karen Garrett, and Nicostrato D. Perez. 2014. *Food Security in a World of Natural Resource Scarcity : The Role of Agricultural Technologies*. Washington D.C., USA: International Food Policy Research Institute.
- Rosegrant, Mark W., Claudia Ringler, Tingju Zhu, Simla Tokgoz, and Prapti Bhandary. 2013. "Water and Food in the Bioeconomy: Challenges and Opportunities for Development." *Agricultural Economics*, 1–12. doi:10.1111/agec.12058.
- Rosenzweig, Cynthia, Joshua Elliott, Delphine Deryng, Alex C. Ruane, Christoph Müller, Almut Arneth, Kenneth J. Boote, et al. 2013. "Assessing Agricultural Risks of Climate Change in the 21st Century in a Global Gridded Crop Model Intercomparison." *Proceedings of the National Academy of Sciences*, December. doi:10.1073/pnas.1222463110.
- Rose, Steven K., Helal Ahammad, Bas Eickhout, Brian Fisher, Atsushi Kurosawa, Shilpa Rao, Keywan Riahi, and Detlef P. van Vuuren. 2012. "Land-Based Mitigation in Climate Stabilization." *Energy Economics* 34 (1): 365–80. doi:10.1016/j.eneco.2011.06.004.
- Schlenker, Wolfram, and David B Lobell. 2010. "Robust Negative Impacts of Climate Change on African Agriculture." *Environmental Research Letters* 5 (1): 014010. doi:10.1088/1748-9326/5/1/014010.
- Schlenker, Wolfram, and Michael J. Roberts. 2009. "Nonlinear Temperature Effects Indicate Severe Damages to U.S. Crop Yields under Climate Change." *Proceedings of the National Academy of Sciences* 106 (37): 15594–98. doi:10.1073/pnas.0906865106.
- Searchinger, Timothy, Ralph Heimlich, R. A. Houghton, Fengxia Dong, Amani Elobeid, Jacinto Fabiosa, Simla Tokgoz, Dermot Hayes, and Tun-Hsiang Yu. 2008. "Use of U.S. Croplands for Biofuels Increases Greenhouse Gases Through Emissions from Land-Use Change." *Science* 319 (5867): 1238–40. doi:10.1126/science.1151861.
- Steinbuks, Jevgenijs, and Thomas W. Hertel. 2013. "Energy Prices Will Play an Important Role in Determining Global Land Use in the Twenty First Century." *Environmental Research Letters* 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. doi:10.1016/j.foodpol.2009.09.002.
- Tubiello, Francesco N., Jean-François Soussana, and S. Mark Howden. 2007. "Crop and Pasture Response to Climate Change." *Proceedings of the National Academy of Sciences* 104 (50): 19686–90. doi:10.1073/pnas.0701728104.
- Tyner, Wallace E. 2008. "The US Ethanol and Biofuels Boom: Its Origins, Current Status, and Future Prospects." *BioScience* 58 (7): 646–53. doi:10.1641/B580718.

UN Population Division. 2000. "World at Six Billion."
 ———. 2013. "World Population Prospects: The 2012 Revision." New York , USA: Population
 Division of the Department of Economic and Social Affairs of the United Nations
 Secretariat. <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. Washington, DC, USA: U.S.
 Department of Energy.
 US EPA. 2015. "Regulations & Standards: Fuels and Fuels Additives." Policies & Guidance.
 Accessed September 11. <http://www.epa.gov/otaq/fuels/renewablefuels/regulations.htm>.
 Westhoff, Patrick. 2010. *The Economics of Food*. New Jersey, USA: Financial Times Press.
 World Bank. 2013. "Food Crisis." April 15.
<http://www.worldbank.org/foodcrisis/bankinitiatives.htm>.
 ———. 2015. "Global Economic Monitor." [http://data.worldbank.org/data-catalog/global-](http://data.worldbank.org/data-catalog/global-economic-monitor)
[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>.

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 (2014), respectively. Future rates use SSP2 projections from the SSP Database v0.5 projections (2012; 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 to 2009 (1971 to 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).

^aGlobal TFP growth rates for the livestock and crop sectors are based on output value-weighted regional rates

FIGURE 1:

Figure 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 (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.

Demand

Supply

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

Figure 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).

774

775

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

787

788

Figure 5. Decadal increments (10-year average) vs. Total global population (annual), 1750-2050.
Source: UNPD (2000; 2013) (bright red bars) SSP Database v0.5 (2012; 2014) (light red bars)