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ABSTRACT

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This dissertation aims to explore the current trends in agricultural productivity and analyse its impact on the global farm and food system. Chapter 2 in this dissertation looks at the current trends in agricultural productivity in India – one most of the populous country in the world. In this chapter, productivity trends in Indian agriculture are examined by looking at changes in Total Factor Productivity – a measure which takes into account all farm outputs and inputs. Estimates in this chapter suggest that TFP growth for the 10-year period – between 1999-2000 and 2009-2010 – steadily grew at the national level. Looking at the 5-year estimates, TFP growth in the early 2000s was sluggish but this poor performance was offset by sharp growth in the late 2000s.

Developments at the global scale ultimately affect world food production and prices. This dissertation develops a new framework for the analysis of productivity, prices, nutrition and land use in the context of a global economy. The Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE) forms the basis for Chapters 3 and 4. In Chapter 3, projections from the SIMPLE model are validated against actual changes in key agricultural variables during the historical period 1961-2006. Given observed growths in population, incomes and total factor productivity, SIMPLE can successfully replicate historical changes in global crop

production, cropland use, global crop yield and price. In Chapter 4, the implications of productivity growth for future global food security are examined using a module which calculates the headcount, prevalence and average depth of malnutrition by looking at the changes in average caloric consumption. Going forward to 2050, population growth is projected to slowdown while biofuel use, per capita incomes and agricultural productivity are expected rise. If TFP growth stagnates, nutritional outcomes would likely worsen, with virtually no reduction in the global headcount of malnourished persons over the 2006-2050 period. Climate change will also have significant implications for nutritional outcomes in hunger stricken regions of the world. Lastly, Chapter 5 outlines the scope for future work and identifies key areas for improvements regarding the studies documented in this dissertation.

CHAPTER 1. INTRODUCTION

1.1: Background and Motivation

In the publication *Limits to Growth* (Meadows, Meadows, Randers, & Behrens, 1972), the Club of Rome forewarned that increasing scarcity in the world's physical resources will limit prospects for economic and population growth in the next century. At that time, the authors even argued that arable land would likely run out by the year 2000 given existing trends in population growth and per capita land requirements. Of course, these concerns have not been borne out, in large part due to the dramatic rise in agricultural productivity over the past decades. From 1961 to 2007, the annual growth in global crop production exceeded that of global population (2.2% vs 1.7%) which experts attribute to rising incomes and steady growth in crop yields (Alexandratos & Bruinsma, 2012; UN Population Division, 2013). A number of factors have helped contribute to the historic rise in productivity including development and adoption of modern crop varieties, increased use of pesticides and fertilizers, and improved access to irrigation (Burney, Davis, & Lobell, 2010; R. E. Evenson & Gollin, 2003; Kendall & Pimentel, 1994).

Commodity spikes felt in recent years have refueled concerns yet again regarding the capacity of modern agriculture to feed the world in the coming decades. However, there are new complexities which are expected to influence the global farm and food system in the near future. Historically, food demand has been fueled by population growth but recent evidence suggests that increasing incomes and changes in dietary patterns are becoming key drivers of food consumption. The world's population is projected to increase at a slower pace, with the growth rate dropping from 1.7% to 0.8% per annum between 1961-2006 and 2006-2051 (UN Population Division, 2013). However, most of the growth in population will occur in developing countries such as India and China wherein per capita incomes are expected to increase sharply (Fouré, Bénassy-Quéré, & Fontagné, 2013). As incomes rise in these regions, dietary upgrading will occur; hence, a large portion of the global population will consume more foodstuffs rich in proteins and fats such as meats, processed food and dairy (Gerbens-Leenes, Nonhebel, & Krol, 2010; Muhammad, Seale Jr., Meade, & Regmi, 2011; Pingali, 2007). In order to meet growing demand for these types of food, the livestock and processed food industries will have to increase production, which in turn translates to greater industrial demand for crop inputs. The growing use of biofuels globally will also contribute to rising in industrial demand for crops since first generation biofuels require crop-based feedstock (Alexandratos, 2008; Malcolm, Aillery, & Weinberg, 2009; Mensbrugghe, Osorio-Rodarte, Burns, & Baffes, 2009; Pimentel et al., 2008).

Given the critical role of productivity growth in meeting global food demands in the coming decades, it is troubling that there is a lack of consensus on whether agricultural productivity is currently rising or slowing down. On one hand, studies which look at crop yields, a partial measure of productivity, argue that yields of key food staples may be reaching their biophysical limits in key regions (Alston, Beddow, & Pardey, 2009, 2010). On the other hand, studies which look at total factor productivity (TFP), an index of output relative to all inputs, suggest that agricultural productivity across the world has increased dramatically over the past decade (Fuglie, 2008, 2012).

Although its impact is uncertain, climate change will undoubtedly influence global agricultural production in the next century. Studies which examine crop yield impacts of climate change focus on the effects of temperature, precipitation and CO_2 fertilization. Depending on the location, temperature and precipitation impacts of climate change may cause crop yields to rise or fall (Tubiello, Soussana, & Howden, 2007). Another aspect of climate change which is important for agriculture is the fertilization effect of rising CO_2 concentrations in the atmosphere. Although the impact of CO_2 fertilization differs across crop types and agro-climatic conditions, it might potentially offset some of the adverse yield impacts of climate change due to temperature and precipitation (Lobell & Gourdji, 2012). Experts also suggest that the risks posed by climate change are likely to be modest into the 2030s but they are expected to become progressively larger in the latter half of this century (Rosenzweig et al., 2013).

1.2: Overall Objectives and Chapter Summaries

Agriculture’s capacity to support the world’s ever-growing populace hinges greatly on sustained productivity growth; thus, the main goal of this dissertation is to explore the current trends in agricultural productivity and analyze its impact on the farm and food system. Specifically, this dissertation provides answers to two key research questions namely: (1) How important is productivity growth in shaping the changes in production, land use and prices? And (2) what are the implications of future productivity growth on nutritional outcomes in the coming decades?

In Chapter 2, the first question is explored at country level by looking at the present state of agricultural productivity in India – one most of the populous country in the world. Historically, India has benefited from the Green Revolution with cereal yields doubling between 1960-1969 and 2000-2009 (FAO, 2013). Similarly, the value of output from pulses, oilseeds and fibers have risen dramatically over the past five decades (Planning Commission, GOI, 2013). However, recent trends suggest that productivity growth has stagnated as gains from the historical Green Revolution continue to diminish, and as investments in Indian agriculture slow down. Yield growth, particularly for cereals, has been virtually flat since the 1990s especially in the northern regions which specialize in food grain production (Gupta & Joshi, 2013; Rada, 2013; A. Singh & Pal, 2010). The sluggish growth is not limited to yields as trends in total factor productivity (TFP) – a measure which account for all farm outputs and inputs – has shown signs of slowing in recent decades (Robert E. Evenson, Pray, & Rosegrant, 1999; P. Kumar & Mittal, 2006; Rada, 2013). In this chapter, latest trends in Indian agricultural productivity growth are examined using Tornqvist-Theil index numbers – a popular approach in TFP growth accounting Specifically, the indices and growth rates of total factor productivity, crop production and farm input use are calculated for the years 1999-2000, 2004-2005, 2009-2010. By examining TFP growth rather than crop yields – a partial measure which only takes into account land input – a broader view of the changes in productivity in Indian agriculture can be examined. The growth accounting approach is also useful in decomposing the sources of output growth according to the contribution between productivity growth and increased input use as well as between extensification (cropland expansion) and intensification (increased yields). The results of the study indicate that TFP for the 10-year period – from 1999-2000 to 2009-2010 – steadily grew at the national level (1.42% per annum). Regional estimates show the dismal performance in the northern region while steady productivity growth has been observed in the rest of India. Furthermore, there is a striking divergence in output and TFP trends between the early and late 2000s. The early 2000s starting from 1999-2000 to 2004-2005 is characterized by stagnant productivity and output growth (0.54% and 0.57% per annum, respectively) which suggests that the stagnation in the Indian crop sector observed during 1990s might have persisted until mid-2000s. In contrast, TFP and output growth grew strongly during the late 2000s across all regions in India (2.47% and 2.93% per annum, respectively). Studies attribute recent improvements in TFP to crop diversification, favorable market prices and recent influx of public investments in agriculture.

Understanding the implications of productivity growth at a global scale requires an economic model of supply and demand for global agriculture. This dissertation develops such a framework, the SIMPLE model. SIMPLE is a partial equilibrium model of global crop production. It has been conceived under the idea that a model should be as a simple possible and yet sufficient enough to capture the key drivers and economic responses which govern global agriculture. In Chapter 3, the SIMPLE model is validated against the changes in global crop production, yields, land use and price during historical period 1961 to 2006. Validation is critical to establish SIMPLE’s credibility in simulating changes in key agricultural variables and also to identify what it does well and what it does poorly. Given observed growths in population, incomes and total factor productivity, the results in this chapter suggest that the SIMPLE model can closely replicate historical changes in global crop production, cropland use, global crop yield and price. The decomposition of drivers also shows that TFP growth is the main driver of change during this historical period by boosting crop production and yields as well as dampening land use and prices. However, the SIMPLE model is not immune to a common problem faced by global models – accurate prediction of regional changes. The model's poor performance on the geographic distribution of production and land use changes over this period suggests that there are likely market barriers and institutional factors which are not captured in SIMPLE. Aside from model validation, this chapter also highlights critical assumptions within existing agricultural models which are likely to have significant impacts on global projections.

The SIMPLE model is used in Chapter 4 to explore the implications of productivity growth for global food security in 2050. To infer nutritional outcomes from SIMPLE's results, a food security module was developed. Specifically, the module calculates the changes in headcount, prevalence and average depth of malnutrition based on regional distributions of food consumption. Going forward, population growth is projected to slow down while biofuel use, per capita incomes and agricultural productivity are expected to rise steadily. The net effect of these diverse drivers is to reduce the global malnutrition incidence, count and gap, particularly in the poorest regions of the world. When TFP growth is removed from the picture, nutritional outcomes worsen, with virtually no reduction in the global headcount over the 2006-2050 period – despite strong growth in average incomes. This highlights the importance of increasing productivity growth in agriculture to temper rising food prices and thereby improve food security in the coming decades. The impact of climate change on future nutritional outcomes is uncertain. Depending on the strength of the yield impacts of CO_2 fertilization, climate change may strengthen or weaken global food security by 2050. Overall, the results from this chapter illustrate the importance of looking at nutritional outcomes based on the distribution rather than focusing only on the changes in average caloric consumption.

Lastly, Chapter 5 outlines the scope for future work and identifies key areas for improvements in the studies documented in this dissertation. Going forward, robust estimates of TFP growth can be calculated by looking at annual data rather than focusing on a limited number of years (i.e. 1999-2000, 2004-2005 and 2009-2010). In addition, it is critical to identify the drivers of crop TFP growth in India and other regions – also linking productivity growth to poverty reduction and improved nutritional outcomes – not just in terms of caloric energy, but also other essential nutrients. This is especially useful for policy makers who are interested in identifying options for sustained productivity growth and its potential gains. To reduce regional discrepancies from SIMPLE's projections, more realistic assumptions concerning international trade are also needed. In the standard version of the model, markets are assumed to be perfectly integrated – yet this is refuted by historical observations during the 1961-2006 period wherein some regions were relatively isolated. Preliminary results using an Armington version of the model which segments markets between domestic and international sources show promise. Other research areas wherein the SIMPLE model can be applied to include: exploration of the trade-offs between food production and the environment, impacts of increased water scarcity in agriculture, and gains from reducing food loss/waste. Finally, projections from the model can be further enriched by conducting a formal sensitivity analysis and constructing distributions of future outcomes in crop production, price, land use and food security given uncertainty in economic responses and in future growth rates of key drivers.

CHAPTER 2. PRODUCTIVITY GROWTH IN INDIAN AGRICULTURE

2.1: Background and Motivation

By mid-century, roughly 17% of the world's populace will reside in India (UN Population Division, 2013). The addition of 400 million more people in the coming decades, coupled with increasing scarcity in arable land, water and other resources will place further pressure on India's agricultural sector. Key to addressing future food demand is sustained productivity growth. From 1961-1969 to 2000-2009, cereal production in India more than doubled with most of the increase coming from yield growth (FAO, 2013). Similarly, the growth rates of output for pulses, oilseeds and fibers have risen dramatically since the 1960s (Planning Commission, GOI, 2013). Although this enabled India to be self-sufficient in food grain production, food consumption has been increasing steadily as evidence by the declining intake of caloric energy and protein since the 1970s (R. Kumar, Bagaria, & Santra, 2014).

Key to the historic rise in Indian agricultural productivity was the Green Revolution. The introduction of high-yielding varieties of wheat and rice, in particular, increased use of modern farm inputs such as fertilizer and pesticides, mechanization and irrigation have helped improve yields and enhance farm incomes (Birthal, Joshi, & Narayanan, 2013; P. Kumar & Mittal, 2006). The influx of investments by both public and private sector in agricultural research and development also contributed to the historic growth in productivity (Robert E. Evenson et al., 1999; A. Singh & Pal, 2010).

However, trends in recent decades suggest that productivity growth has stagnated as gains from this historic Green Revolution continue to diminish and as public investments in Indian agriculture slow down. Indeed, crop yield growth particularly for cereals has been flat during the 1990s (Gupta & Joshi, 2013; Rada, 2013; A. Singh & Pal, 2010). The sluggish growth is not limited to yields as trends in total factor productivity (TFP) – a measure which account for all farm outputs and inputs – also has shown signs of slowing (Robert E. Evenson et al., 1999; P. Kumar & Mittal, 2006; Rada, 2013). Within India, productivity growth rates are diverse as states which rely on rain-fed agriculture typically exhibit slower output growth on average (A. Singh & Pal, 2010).

In light of these issues, this chapter provides an assessment of recent productivity trends in Indian agriculture by calculating indices and growth rates of total factor productivity (TFP), crop production and farm inputs using state-level data on crop production and cultivation costs for the years 1999-2000, 2004-2005, 2009-2010. Unlike crop yields – a partial measure of productivity which only takes into account land inputs – TFP provides a broader measure of productivity trends in India’s crop sector by accounting for all outputs and inputs. Estimates of TFP growth in this study are calculated at both the national and regional level. Regional assessment is especially relevant for policymakers who are concerned about the implications productivity growth for poverty, food security as well as sustainability of agriculture within the poorest regions of India.

This chapter is arranged as follows. It starts with a review of recent studies which examined the evolution of agricultural productivity growth within India. The data and methodology used in this chapter are then outlined. Following the literature, the

Tornqvist-Theil index numbers are used to calculate the indices and growth rates of total factor productivity, outputs and inputs. Under this approach, crop output growth can be decomposed by looking at the contribution by each crop, between TFP growth and input use as well as between extensification (i.e. cropland expansion) and intensification (i.e. crop yield growth). Finally, the results and conclusions of this study are discussed.

2.2: Review of Recent Literature

Due to data constraints, there are only a few studies which examine total factor productivity at the sub-national level. Evenson, Pray and Rosegrant (1999) utilized district level data spanning 13 different states for the period 1956 to 1987. Using the Tornquist-Theil indices, the authors computed TFP growth rates for 4 aggregate regions. Around 18 crops were covered in the study including food staples such as rice, wheat, millet and maize. On the other hand, farm inputs used in the study were rain-fed and irrigated land, human and animal labor, farm machinery and fertilizer use. The authors estimated that TFP growth rate at the national level was around 1.13% per annum during the period 1956-1987 with sluggish growth during 1977-1987 relative to 1966-1976 (1.05% vs 1.39% per annum, respectively). The authors argued that the slowdown is due the diminishing returns from intensive use of modern farm inputs. Within India, the stagnation in productivity growth between 1966-1976 and 1977-1987 is quite evident in the western region (slowing from 1.60% to 0.39% per annum, respectively). To the contrary, productivity growth rates increased in the northern and southern regions (from 1.32% and 1.01% to 1.57% and 1.50% per annum, respectively). The authors attributed the sharp growth in the southern region to “catching up” since this region lagged in adapting Green Revolution technologies. The authors also explored the determinants of TFP growth and found that increased spending in agricultural research and development, farm management and extension as well as irrigation expansion helped improve agricultural TFP growth during 1956-1987.

Fan, Hazell and Thorat (1999) explored the linkages between poverty, TFP growth and government spending in agriculture. Using data from crop and livestock sectors, the authors computed the Tornquist-Theil output and input indices and estimated TFP growth rates at the state-level for the period 1970-1994. The results indicated that agricultural TFP grew by around 1.75% per annum for the whole period with a slightly reduced growth rate during the 1990-1994 period (2.52% vs 2.29% per annum, respectively). Results at the state level show widespread slowdown in TFP growth. Around 9 out of 16 states showed either stagnant or declining productivity between 1980-1989 and 1990-1994. Determinants of TFP growth identified by the authors include expenditures in agricultural research and development, investments in roads as well as education. The authors also found evidence linking increased agricultural productivity to reductions in poverty.

More recently, Kumar, Kumar and Mittal (2004) examined the productivity trends in the Indo-Gangentic Plains using district-level data for the period 1981-1982 to 1996-1997. The authors noted that this region is favorable to farming as it is endowed with suitable agro-climatic condition as well as adequate water resources. In the study, the authors used crop and input data for 94 districts covering 5 key states namely Punjab, Haryana, Uttar Pradesh, Bihar and West Bengal. Growth rates computed from the Tornquist-Theil indices suggest steady TFP growth for the whole region during this period (1.21% per annum). States which exhibited sharp productivity growth include West Bengal and Haryana (around 3.08% and 2.22% per annum, respectively). Among the states, productivity in Uttar Pradesh stagnated growing by less than 1% per annum. The authors also noted that TFP growth for all 5 states declined between the periods 1981-1982 to 1990-1991 and 1990-1991 to 1996-1997. Agricultural extension, improvement literacy and investments in infrastructures were mentioned as key determinants of productivity growth during this period.

Using state level cost of cultivation data, Kumar and Mittal (2006) used the Tornqvist-Theil approach to calculate TFP growth rates for principal crops starting from 1971 to 2000. The results of the study suggest that at the national level productivity growth has been sluggish for key staples such as wheat and coarse grains and for high-value crops between 1971-1986 and 1986-2000. Within India, the slowdown in productivity is evident in the northern and southern states. Northern states – such as Punjab and Haryana wherein modern agriculture is relatively well developed – displayed either declining or stagnating TFP growth. Even southern states wherein TFP grew strongly during 1971-1986 exhibited decreasing TFP growth in 1986-2000. The authors argued that the slowdown in recent decades is likely due to the diminishing returns from the historical Green Revolution and the observed decline in public investments in agriculture.

More recently, Rada (2013) examined composite output, input and TFP growth for the combined crop and livestock sector using Tornqvist-Theil indices calculated at the national, regional and state-level. Unlike Kumar and Mittal (2006), the author complied data on farm outputs and inputs from several sources. Outputs covered in the study included grains, pulses, horticulture & spices, oilseeds, specialty crops and animal products while inputs include labor, land and land quality, materials inputs and capital. From 1980 to 2008, the estimated TFP growth is around 1.90% per annum with only one state showing signs of stagnating productivity growth. The author noted that increased crop diversification from traditional food staples to high value crops such as fiber and oilseeds helped improve TFP trends during the 2000s. However, there are some regions wherein productivity growth has slowed down. In particular, TFP growth in the northern states – states which still specialize in intensive cereal production – has been sluggish in recent years.

To summarize the literature, there is strong evidence that TFP growth in Indian agriculture increased greatly during the early years of the Green Revolution (i.e. 1960s to 1970s). However, productivity has slowed down since then, especially during the 1990s. Authors argued that the slowdown can be attributed to the diminishing returns from intensive use of modern farm inputs, declining public investments in agriculture, slowdown in agricultural research and development, as well as lack of crop diversification. This trend has been reversed during the 2000s, at least at the national level. Analysis at the state-level shows heterogeneity in productivity growth within India. In particular, TFP growth in the northern states which benefited greatly from the historical Green Revolution has slowed down. On the other hand, productivity in southern and western states has been rising in recent times as these states catch-up with the rest of India and diversify their production towards higher value crops.

2.3: Methodology and Data

Following the literature, the Tornqvist-Theil approach is used in calculating the index numbers of input, output and TFP as well as their corresponding growth rates. Because it is convenient to implement, the Tornqvist-Theil index number is widely popular in the growth accounting and TFP literature. It also has several useful properties. Diewert (1976) argued that if the underlying specification of the production function is translog then the discrete Tornqvist-Theil indices are analogous to the continuous Divisia indices which has been traditionally been used to quantify technical change (Griliches & Jorgenson, 1966; Schultz, 1961). Furthermore, Caves, Christensen and Diewert (1982) found that with the translog production function the Tornqvist-Theil indices approximate the geometric mean of Malmquist indices – index numbers which are typically estimated using parameteric and non-parameteric methods (Färe, Grosskopf, & Lovell, 1994; Kumbhakar & Lovell, 2003). Tornqvist-Theil index is "exact" that is it directly related to the underlying production function (i.e. it is equal to the ratio of the translog production function between two periods). Moreover, since the translog function is a good second order approximation any twice-differentiable production function, the Tornqvist-Theil index is considered as a "superlative" index (Diewert, 1976; Hulten, 2001). Following Evenson, Pray and Rosengrant (1999), TFP growth between two time periods (t, t-1) is computed in this study using the following equation:

$$\ln\left[\frac{TFP_t}{TFP_{t-1}}\right]=\sum_k \frac{1}{2}\left[R_{k,t}+R_{k,t-1}\right]\ln\left[\frac{Y_{k,t}}{Y_{k,t-1}}\right]-\sum_j \frac{1}{2}\left[C_{j,t}+C_{j,t-1}\right]\ln\left[\frac{X_{j,t}}{X_{j,t-1}}\right]$$

wherein R_k is the revenue share of crop k, Y_k is the quantity of crop k produced, C_j is the cost share of input j and X_j is the quantity of input j used.

Implementation of the Tornqvist-Theil index number requires data on quantities and prices for both inputs and outputs. Data on area, yields and production are taken from the Indian Ministry of Agriculture (2014) while information on input use and costs are derived from the Cost of Cultivation Surveys (IASRI, 2008) for the years 1999-2000, 2004-2005 and 2009-2010. These surveys are based on the cost of cultivation data sampled at three administrative levels (i.e. by *tehsil,* village and holding). In total, data for 3 periods from 16 states, 18 crops and 12 inputs are used (see Appendix A). For convenience, state level estimates of input, output and TFP growth rates are aggregated at the national level and for four regions namely the North, South, East and West regions using the mapping by Kumar and Mittal (2006) [1] as a guide. Estimates at the state-level are summarized in Appendix B.

2.4: Results

The results for the 10-year period from 1999-2000 to 2009-2010 provide an overview of the trends in output, input and TFP growth in the Indian crop sector. At the national level, most of the total revenue in the crop sector comes from the northern and western regions (around 35% and 36%, respectively) while revenue shares from the southern and eastern regions are relatively small (roughly 19% and 10%, respectively). This suggests that trends in production in the northern and western regions heavily influence over-all growth of the Indian crop sector. To understand the patterns of crop production in India, it is important to examine the revenue shares by crop (Figure 2.1).

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[1] North includes Himachal Pradesh, Haryana, Punjab and Uttar Pradesh. South consists of Andhra Pradesh, Karnataka, Kerala and Tamil Nadu. East consists of Assam, Bihar, Orissa and West Bengal. West includes Gujarat, Madhya Pradesh, Maharashtra, and Rajasthan.

Figure 2.1 clearly shows crop specialization in some regions. Specialization in cereal production is observed in the northern, eastern and southern regions wherein cereal revenue shares are above 65%. Note that production of cereal grains have been prioritized in the past due to concerns regarding food security. The contribution of cereal in the northern region is particularly high since cereal production in this region has been the focus of the historical Green Revolution (Fujita, 2010). It is interesting to note that revenue shares in the western region is much more diverse as the combined contribution of oilseed and fiber crop is about as large as the contribution of cereals (20%, 20% and 40% respectively). As production neared self-sufficiency levels there has been a shift from food staples towards high-value crops. For example, increased oilseed production has been fueled by price incentives, increased market protection and favorable government programs particularly during the 1990s (Hazra, 2001). Cotton production also experienced expansion in recent decades due to increased demand from the domestic textile industry and from exceptional productivity growth which some argue is linked to the adoption of Bt cotton varieties (Gruere & Sun, 2012; A. Singh & Pal, 2010). Looking at the national shares, 63% of total crop revenue in India comes from cereal production while the rest comes from high-value crops such as sugar cane, oilseeds and fiber crops.

Figure 2.2 illustrates the cost shares of crop production at the national and regional level from 1999-2000 to 2009-2010. Almost half of the cost of crop production in the northern region is due to land input use. Cost share for human labor is largest in the southern and eastern regions at around 36% and 40% respectively. Although the cost share for 'animal + machine' labor is highest in the western region (at around 17%) it is still well below the shares of land and human labor. The contribution of material inputs such as seeds and fertilizer + manure are relatively small for both the national and regional level. From the figure, it is obvious that crop production in India is still reliant on traditional inputs with land and human labor cost shares at roughly 41% and 31% respectively.

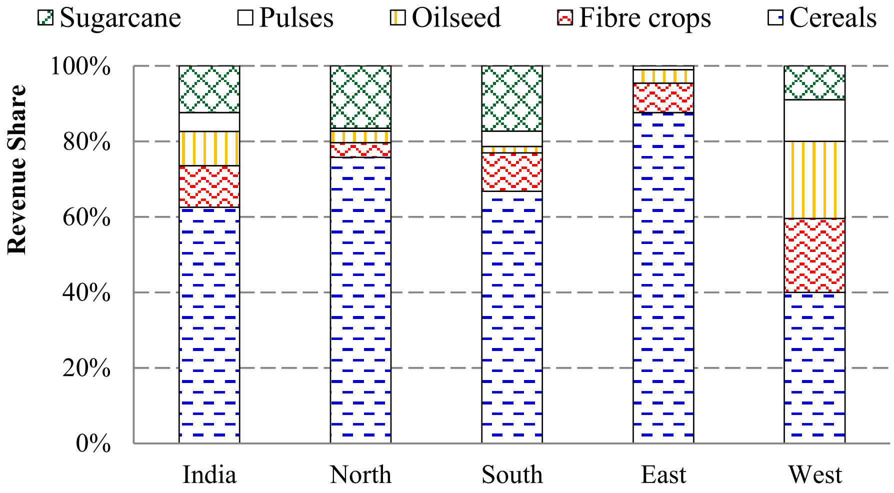

Figure 2.1: Revenue Shares by Crop: 1999-2000 to 2009-2010

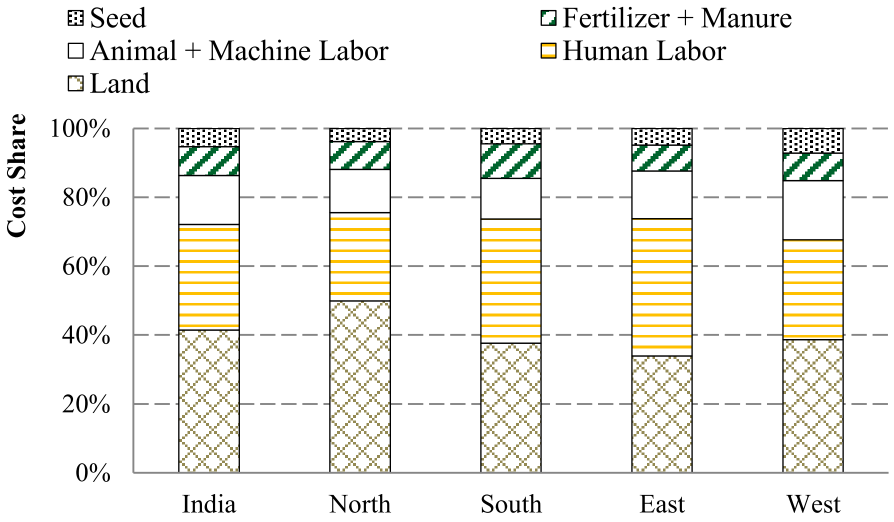

Figure 2.2: Cost Shares by Input: 1999-2000 to 2009-2010

Growth rates for TFP, output and input for the 10-year are summarized in Table 2.1. India is an extremely heterogeneous country and regional performance differs widely. In particular, TFP has been rising in all regions except in the north wherein productivity growth has been flat. Regions which displayed exceptional growth in TFP include the western and eastern regions (more than 1.9% per annum). Total factor productivity grew in the eastern and southern regions due to the reduction in input use coupled with relatively stagnant output growth. Contrary to this, output grew strongly while input use was relatively unchanged in the western region which is consistent with the gains from diversification towards higher value output. It is concerning that productivity in the northern region stagnated during this period (with a TFP reduction at around 0.17% per annum) with input use outpacing output growth. This finding is consistent with the literature regarding the slowdown of productivity growth in the northern region wherein there is diminishing returns from increased input use particularly for cereal production (P. Kumar & Mittal, 2006; S. Singh, Park, & Litten-Brown, 2011). Moreover, continuous soil degradation and increasing scarcity of water resources have also led to the stagnant agricultural growth in this region (Joseph, 2004). Growth in other regions more than offset the poor performance in the north; thus, at the national level productivity in the crop sector steadily rose – with TFP growing by 1.42% per annum – from 1999-2000 to 2009-2010. Output growth overtook input use during this 10-year period (1.72% vs 0.30% respectively). These estimates suggest that the India's crop sector may have recovered from the observed stagnation in TFP growth during the 1980s and 1990s (Fan et al., 1999; P. Kumar et al., 2004).

Table 2.1: Ten-Year Growth Rates of Output, Input and TFP: 1999-2000 to 2009-2010

Time Period 1999-00 to 2009-10 (10-years)	Average Annual Growth Rate TFP	Output	Input
National	1.42%	1.72%	0.30%
North	-0.17%	3.15%	3.32%
South	1.03%	-0.07%	-1.09%
East	2.04%	-0.46%	-2.50%
West	1.91%	1.90%	-0.01%

Figure 2.3 shows the sources of output growth during the period 1999-2000 to 2009-2010. The top panel shows the contribution to output growth by crop while the middle panel decomposes output growth between land expansion (extensification) and yield growth (intensification). Lastly, the bottom panel decomposes output growth according to input use and TFP growth. Starting with the top panel, the contribution of cereals to regional crop output growth is negative except in the northern region wherein cereals dominated the output growth from other crops. On the other hand, fiber crop production helped boost crop output in all regions – particularly in the southern and western region – highlighting the benefits of cultivating high value crops. Given these regional trends, crop output growth at the national level is mainly driven by fiber crop and cereal production during this 10-year period.

The contribution of land expansion and yield growth to output growth is illustrated in the middle panel of Figure 2.3. Both area expansion and yield growth are key sources of output growth in the northern region wherein the cost share of land is relatively high compared to other inputs. Output growth in the western region is mainly due to intensification. The southern and eastern regions experienced flat output growth due as cropland use contracts. At the national level, intensification contributed more to output growth than area expansion during this 10-year period. Finally, output decomposition by input use and TFP growth is shown in the bottom panel of Figure 2.3. It is interesting to note that the impact of TFP on output growth varies across regions. In the north, TFP is flat with output growth mainly driven by increased input use. Contrary to this, output growth in other regions is mainly due to rising TFP; thus TFP growth is the main driver of output growth in the Indian crop sector during this period while the contribution of input use is negligible.

Before proceeding further, it is important differentiate the contribution of yield and TFP to output growth. Within the growth accounting framework, any changes in output which cannot be explained by area expansion is attributed to yield growth; thus, the impact of TFP – along with other non-land inputs – on output growth is folded within the contribution of yield growth. Given this, trends in yield growth do not necessarily reflect trends in TFP. For example, note that in Figure 2.3 TFP in the southern and eastern regions is rising (bottom panel) despite flat yield growth (middle panel). Likewise, TFP growth is stagnant in the northern region despite strong yield growth. Each productivity measure captures different aspects of the farm and food system. Total factor productivity growth dampens the costs of production for producers resulting in lower food prices for consumers while yield growth is key for mitigating future agricultural land use expansion (Havlik et al., 2013; R. B. Singh, Kumar, & Woodhead, 2002).

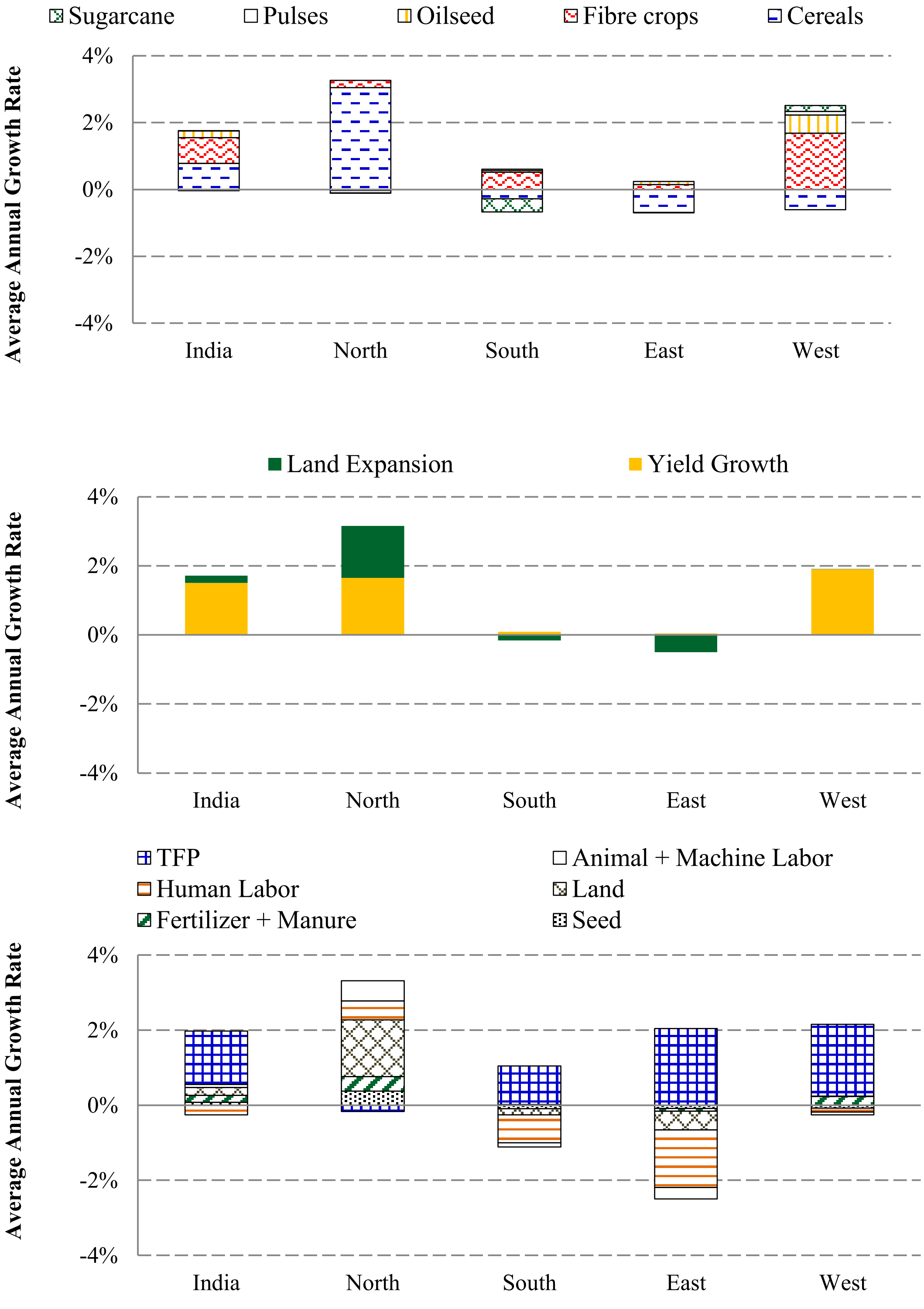

Figure 2.3: Decomposition of Output Growth: 1999-2000 to 2009-2010

Although the 10-year growth rates show a grim trend in both output and total factor productivity, examination of the 5-year growth rates from 1999-2000 to 2004-2005 (early 2000s) and from 2004-2005 to 2009-2010 (late 2000s) indicate renewed growth in the Indian crop sector. Table 2.2 summarizes the estimates of TFP, output and input growth during the early and the late 2000s. The divergence in the growth rates between the two periods is quite remarkable. In the early 2000s, TFP reduction (-1.95% per annum) is observed in the northern region as input use outpaced output growth (6.71% vs. 4.76% per annum). On the other hand, there are signs that the crop sector for other regions contracted as both growth rates of output and input fall. In the southern region, output growth contracted faster than input use which resulted in flat TFP growth during the early 2000s. At the national level, total factor productivity, output growth and input use are relatively flat (0.54%, 0.57% 0.03% per annum, respectively). As mentioned in the literature, Indian agriculture during the 1990s is characterized by the poor performance due to diminishing gains from current technologies (Robert E. Evenson et al., 1999) along with relatively low public investments in agriculture (Birthal, Joshi, Negi, & Agarwal, 2014; Pal, Rahija, & Negi, 2012). And given the 5- year estimates, it is likely that the dismal trend in the 1990s might have persisted in the early 2000s.

Steady growth rates of output and TFP during 2004-2005 to 2009-2010 show some evidence of renewed growth in the Indian crop sector (Table 2.2). High TFP growth rates are observed in the eastern and western regions (around 4.06% and 3.55% per annum, respectively). Productivity in the northern region is growing, but at a slower rate compared to other regions (by 1.57% per annum). Both output and input expanded in the western region with output growth overtaking input use while in other regions, output grew strongly (by more than 1.5% per annum) despite the slowdown in input use. At the national level, TFP grew by 2.47% per annum as output rose sharply while input use remained flat (2.93% and 0.46% per annum respectively) which suggest renewed vigor in the Indian crops sector. As noted Birthal et al. (2014), key factors which might have contributed to the increase in output growth during the late 2000s include crop diversification as well as favorable global prices for crops especially after the 2007-2008 commodity price spikes. Technological improvement – a long-run source of productivity growth – might have also helped increase output growth but its contribution has been declining since the 1990s.

Table 2.2: Five-Year Growth Rates of Output, Input and TFP: 1999-2000 to 2009-2010

Time Period	Average Annual Growth Rate TFP	 Output	 Input
1999-00 to 2004-05 (5-years)			
National	0.54%	0.57%	0.03%
North	-1.95%	4.76%	6.71%
South	-0.64%	-2.57%	-1.92%
East	0.22%	-4.81%	-5.03%
West	0.82%	-1.04%	-1.87%
2004-05 to 2009-10 (5-years)			
National	2.47%	2.93%	0.46%
North	1.57%	1.46%	-0.11%
South	2.99%	2.53%	-0.46%
East	4.06%	3.74%	-0.33%
West	3.55%	5.22%	1.68%

Figure 2.4 compares the national-level crop TFP indices with those from Rada (2013) which cover all of agriculture, including fruits and vegetables and livestock, in order to crosscheck if the estimates in this chapter are consistent with those in the literature. It is not surprising that the TFP indices by Rada rose faster during this 10-year period since it includes staple crops, specialty crops and livestock production, and the

latter two appear to have experienced more rapid productivity growth over this period. The author also used different data sources. However, TFP trends in the literature are generally consistent with the findings in this chapter and that the early-2000s is characterized by slow growth in agriculture while the late 2000s showed resurgence. Although trends at the national level are broadly reflected by the estimates in this chapter, the results at the regional-level diverge from those in the literature particularly in the northern and southern region (Appendix C). These discrepancies highlight the sensitivity of TFP estimates to output and input coverage as well as data sources.

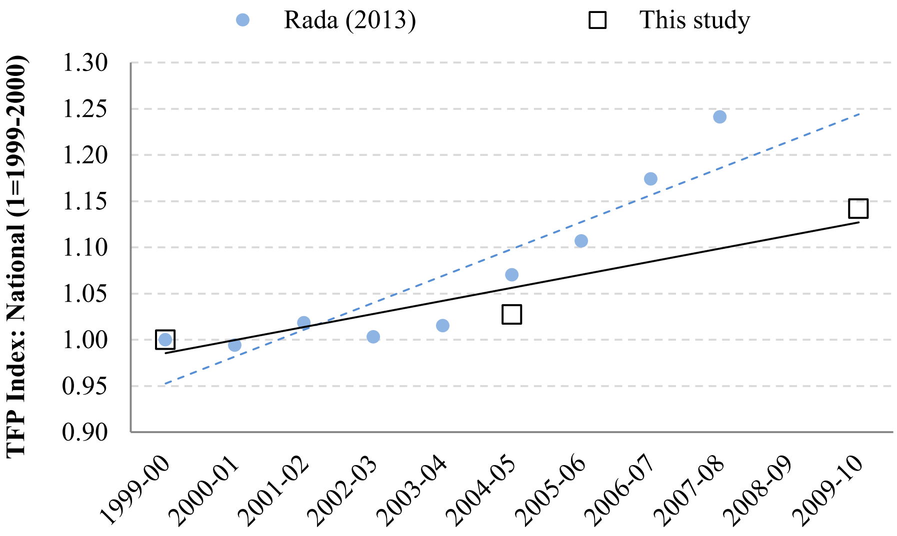

Figure 2.4: Comparison of TFP estimates: National-level

Decomposition of output growth between the early and late 2000s is illustrated in Figures 2.5, 2.6 and 2.7. In Figure 2.5, output growth is decomposed by crop. From 1999-2000 to 2004-2005, it is clear that the production of cereals and sugarcane fell drastically in the southern, eastern and western regions. Indeed, cereal production in the eastern region fell sharply by 5.01% per annum. It is interesting to note that the contribution of oilseeds and fiber crops to total output growth is positive during this period which provides further evidence of the potential gains from crop diversification. With improved performance in the crop sector during the late 2000s, output growth at the national level mainly comes from cereals, sugarcane and fiber crops. At the regional level, output growth in the northern and eastern regions are mainly driven by cereal production while in the southern and the western regions, both sugarcane and fiber crops contributed significantly to output growth.

At the national level, output growth was relatively flat during the early 2000s with negligible contribution of both area expansion and yield growth (Figure 2.6). Except in the northern region wherein area expansion and yield growth rose sharply, output in the rest of India was declining due to reduction in yield growth. Looking at the late 2000s, yield growth is the main driver of overall output growth. It is interesting to note that the contribution of intensification in output growth is highest in the western region wherein crop production is more diverse while it is lowest in the northern region, a region which specializes in cereal production. This resonates with the findings in literature regarding the returns from crop diversification and the dwindling opportunities to increase productivity in regions which specialize in cereal production. Finally, the contribution of TFP and input use to output growth during the early and late 2000s is illustrated in Figure 2.7. Consistent with the previous findings, the contribution of TFP growth to output growth during the period 1999-2000 to 2004-2005 is quite negligible at the national level. Increased use of inputs in the northern region – particularly in land and ‘animal + machined labor’ – are key sources of regional output growth. Output growth in the rest of India declined mainly due to the contraction in input use during the early 2000s. In contrast, TFP growth remains a key driver of output growth during the period 2004-2005 to 2009-2010 particularly in the southern, eastern and western regions. In the north, TFP growth is a still key source of output growth but its contribution is relatively smaller than the impact of TFP growth in other regions.

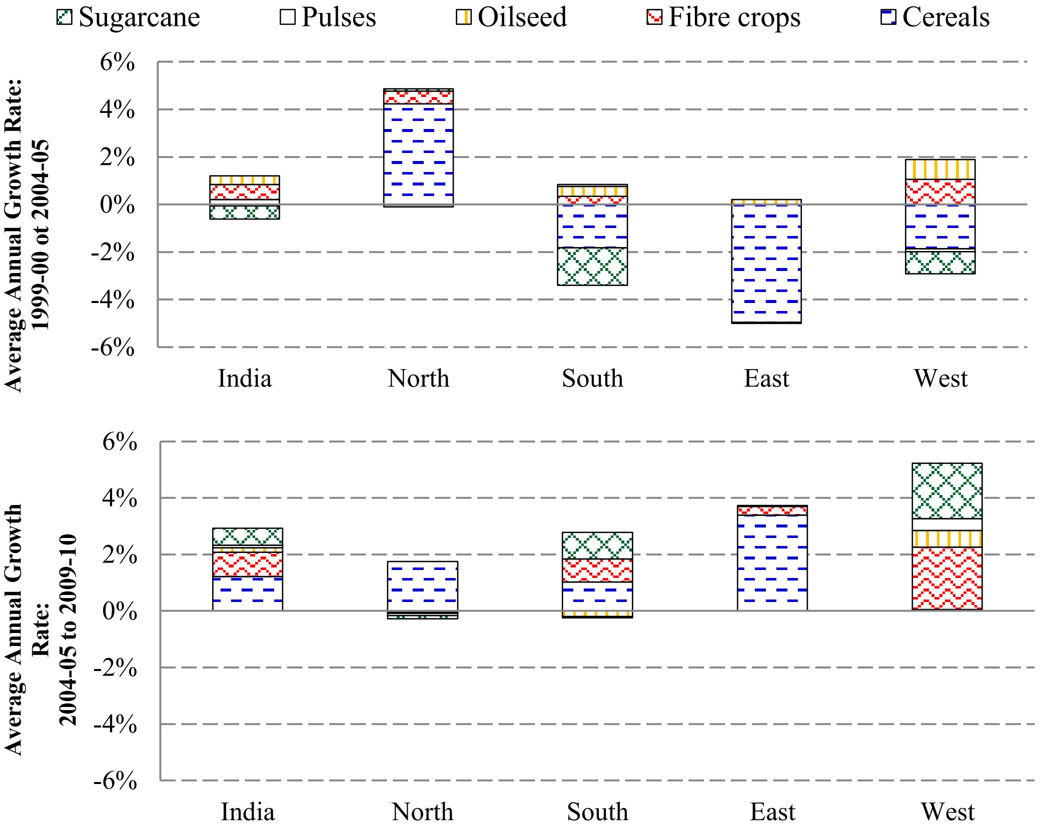

Figure 2.5: Decomposition of Output Growth by Crop: Early vs. Late 2000s

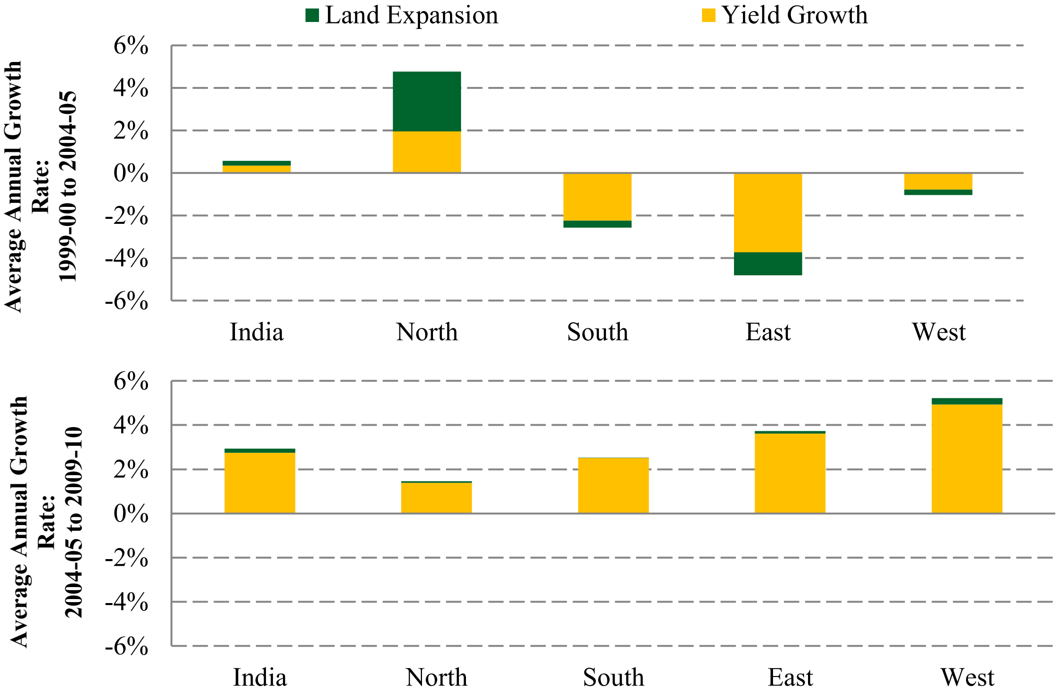

Figure 2.6: Decomposition of Output Growth by Margins: Early vs. Late 2000s

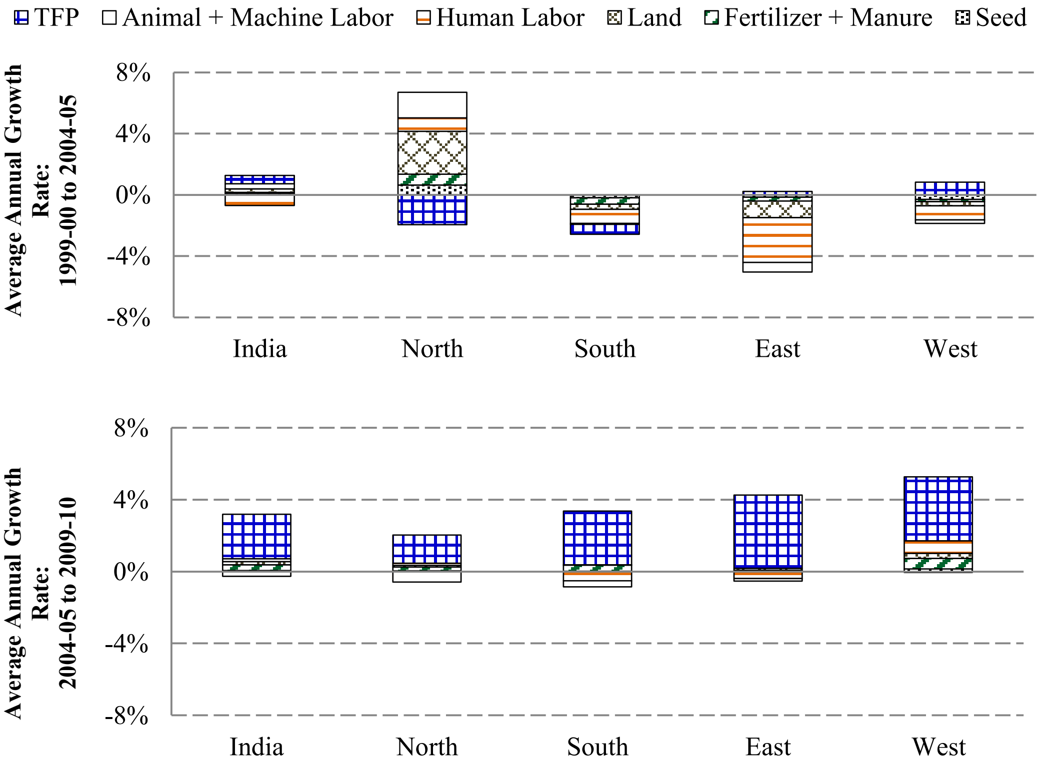

Figure 2.7: Decomposition of Output Growth by Inputs and TFP: Early vs. Late 2000s

2.5: Summary and Conclusions

In this chapter, the growth rates of output, inputs and total factor productivity during the period 1999-2000 to 2009-2010 are examined. There is great heterogeneity in productivity growth within India as evidenced by the regional estimates. In particular, TFP growth in the northern region has been flat – dampening some of gains in TFP observed in other regions. Among the regions in India, the northern region has benefitted greatly from the historical Green Revolution.

However, 10-year trends estimated in this chapter show that, output growth in this region relies heavily on increased input use. This finding resonates with the literature and it is likely that this region may have exhausted most of the opportunities to increase productivity given current technologies. The poor performance in the north offset some of the steady growth in TFP observed in other regions; thus, TFP growth at the national level remained flat over this 10-year period.

Looking at the decomposition of output growth, the contribution of cereals is still positive while high-value crops such as fiber crops are becoming new sources of output growth during the period 1999-2000 to 2009-2010. The contribution of fiber crops is particularly high in the western region – a region wherein crop production is relatively more diversified. This provides further support regarding the potential gains from diversifying crop production away from cereals towards high value crops such as fiber crops.

The 10-year period conceals the divergence in output and TFP trends between the early and late 2000s. Looking at the regional level, there is strong TFP reduction in the northern region during the early 2000s as output growth fell behind the increase in input use. In other regions, output fell as much as the reduction in input use. When aggregated at the national level, these results indicate that the early 2000s is characterized by stagnant productivity and output trends. This suggests that the contraction in the Indian crop sector during the 1990s might have persisted up to the early 2000s.

In contrast to the early 2000s, output and productivity grew strongly during the late 2000s which imply renewed growth in India's crop sector. Output grew fastest in the western region although it is coupled with steady rise in input use. Both output and TFP growth are relatively slower in the northern region. The decomposition of output growth shows that all crops contributed to increased output during 2004-2005 to 2009-2010. Intensification dominated the impact of area expansion as yield growth led to the majority of the output increase during this period.

Factors which might have led to the favorable trends observed during the late 2000s include continued diversification of crop production towards high value crops such as fiber crops and oilseeds and relatively high crop prices. In the long-run, the northern and eastern regions – regions, which specialize in cereals and are currently experiencing slowdown in productivity, could potentially benefit by diversifying their production mix towards high value crops. Going forward, continued public investments in the agricultural sector and technological innovations are necessary to ensure steady growth in Indian agriculture in the coming decades.

The findings in this chapter show that productivity growth is important for sustained increases in crop production without significant growth in input use. Of course, TFP growth is just one of the key drivers of agriculture. A more thorough discussion of the implications of productivity growth – especially at a global scale – requires a formal economic model of agricultural supply and demand. In the next chapter, the SIMPLE model is introduced and is used to explore how productivity growth along with other drivers helped shape the historical changes in crop production, land use and prices.

CHAPTER 3. LOOKING BACK TO MOVE FORWARD ON MODEL VALIDATION: INSIGHTS FROM A GLOBAL MODEL OF AGRICULTURAL LAND USE[2]

3.1: Background and Motivation

Global agricultural models are indispensable tools in policy-making. These models have been traditionally used to assess the impacts of foreign and domestic economic policies on food production, consumption, prices and land use. However, in the past decade interest has grown in applying agricultural models to assess climate change impacts and land-based mitigation options. This is important, since land-based emissions account for more than one-quarter of global greenhouse gas (GHG) emissions (Baumert, Herzog, & Pershing, 2005), and could potentially supply 50% of economically efficient abatement at modest carbon prices, with most of this abatement coming from slowing the rate of agricultural land conversion (Golub et al., 2012). Therefore, projections of agricultural land use are essential inputs to climate change and GHG mitigation studies. However, the value of such projections hinges on the scientific credibility of the underlying models. And this depends on model validation – an area in which global models of agriculture have been notably lacking to date. Currently, there is great interest in redressing this limitation. However, the range of models currently in use is quite wide

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[2] This chapter draws heavily from Baldos, U. L. C., & Hertel, T. W. (2013). "Looking back to move forward on model validation: insights from a global model of agricultural land use". *Environmental Research Letters*, 8(3), 034024. doi:10.1088/1748-9326/8/3/034024 and from a working paper by Baldos, U.L.C, & Hertel, T. W. (2012). The results in this chapter are based on an updated version of the SIMPLE model.

and the challenge of validation is a daunting one. Agricultural models can be loosely classified into two broad categories. On the one hand, there are ‘partial equilibrium’ models which specialize on the agricultural sector (Havlik et al., 2013; Lotze-Campen et al., 2008; G. Nelson et al., 2010). Often these models explicitly incorporate biophysical linkages between crop production and environmental variables. On the other hand, ‘general equilibrium’ models place agriculture within the context of the global economy, with most economic variables being endogenous to the model (Golub et al., 2012; Gurgel, Reilly, & Paltsev, 2007; Wise et al., 2009). This makes validation more challenging and therefore most general equilibrium validation exercises focus on a few key variables or sectors (Beckman, Hertel, & Tyner, 2011; Keeney & Hertel, 2005).

Successful model validation is also confounded by the fact that agricultural models must predict human behavior, as well as market interactions between economic agents. In particular, human decision making with respect to land use is context dependent, prone to change over time and poorly understood (Meyfroidt, 2012). And even when these relationships are known, there is a lack of global, disaggregated, consistent, time series data for model estimation and evaluation of the full modeling system. In response to this challenge, some modelers have proposed a more targeted approach to validation by focusing on a few key historical developments or ‘stylized facts’ (Schwanitz, 2013). This suggests a useful way forward on validating agricultural models. Without doubt, the most important fact about global agriculture over the past 50 years has been the tripling of crop production, with only 14% of this total coming at the extensive margin in the form of expansion of total arable lands (Bruinsma, 2009). This remarkable accomplishment contributed significantly to moderating land-based emissions

(Burney et al., 2010). Whether or not this historical performance can be replicated in the future is a central question in long-run analyses of global agriculture (Havlik et al., 2013; Wise et al., 2009). Yet studies which relate model projections to historical performance are quite sparse. For some models, evaluation of past agricultural projections has been mainly focused on crop production (McCalla & Revoredo, 2001) and there is a dearth of literature tackling the issue of reproducing historical cropland use (Lotze-Campen et al., 2008). It is critical to evaluate long-run global agricultural models of land use to see how well it can capture the historical experience. And this chapter illustrates the opportunity and the challenge of undertaking such a validation exercise using the SIMPLE model of global agriculture (Simplified International Model of agricultural Prices Land use and the Environment). As its name suggests, this framework is designed to be as simple as possible while capturing the major socioeconomic forces at work in determining global cropland use. This makes it a useful test-bed for the design of validation experiments.

This chapter starts with the documentation of the SIMPLE model followed by a discussion regarding the model's base data and parameters. The model is then tested against the historical period: 1961-2006, illustrating what it does well and what it does poorly. Using this 45-year period as a laboratory, and focusing on the dimensions along which the model performs well, various model restrictions which are embedded in many agricultural models are imposed in SIMPLE to see how these restrictions alter the model's historical performance. These experiments serve to highlight which assumptions are likely to be most important from the point of view of cropland use. Finally, the chapter concludes with suggestions on how best to advance the state of knowledge about modeling agricultural land use at the global scale.

3.2: SIMPLE: A Global Model of Agriculture

Unlike other global agricultural models which are generally more complex and disaggregated, the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE) is parsimonious and tractable. It has been designed under the principle that a model should be no more complex than is absolutely necessary to understand the basic forces at work. At the core of SIMPLE is the theoretical model developed by Hertel (2011). He proposed a simple static partial equilibrium model in order to analyze the long run drivers of supply and demand for global agricultural land use and crop price. There are three exogenous drivers in this model. Firstly, the growth in aggregated demand for agricultural products (Δ_A^D) captures the increasing global demand for food consumption and for feedstock use by the global biofuels industry. Secondly, a shifter of the global supply of agricultural lands (Δ_L^S) consists of factors which limit the availability land inputs. These include the encroachment of urban lands into croplands and growth in the demand for land in ecosystem services. Finally, changes in agricultural productivity (Δ_L^D) influences the derived demand for agricultural lands. Solving this model for the long run equilibrium percentage changes in global agricultural land use (q_L^*) and price (p_A^*), as functions of these three exogenous drivers gives the following expressions:

$$q_L^* = (\Delta_A^D + \Delta_L^S - \Delta_L^D) / (1 + \eta_A^{S,I} / \eta_A^{S,E} + \eta_A^D / \eta_A^{S,E}) - \Delta_L^S \qquad (1)$$

$$p_A^* = (\Delta_A^D + \Delta_L^S - \Delta_L^D) / (\eta_A^{S,I} + \eta_A^{S,E} + \eta_A^D) \qquad (2)$$

As noted by Hertel (2011), the long-run changes in agricultural land use and price are mediated by the three margins of economic response to scarcity: the price elasticity of demand for agricultural products, η_A^D, the response of yields to higher commodity prices – dubbed the intensive margin of supply response, $\eta_A^{S,I}$, and the extensive margin of supply response (area response to commodity prices), $\eta_A^{S,E}$. For a given set of exogenous shocks, the larger are the former two elasticities, relative to the latter, the more modest the global change in agricultural land use. Similarly, the long run change in agricultural price is dampened as any or all of these three economic margins become larger. In developing SIMPLE, these three margins of economic response are incorporated while introducing greater empirical detail by disaggregating the sources of demand and supply for agricultural products (Figure 3.1). A complete listing of equations variables, parameters and model code are provided in the Appendix C to F.

In SIMPLE, per capita food consumption is defined for four commodities, including both non-food and food products, differentiating between direct consumption of crops, and indirect consumption of crops through the demand for livestock products and processed food products. The latter two categories are important since: (1) demand for these food commodities are expected to rise with growing incomes, especially in the developing world, and (2) increases in the efficiency with which crops are used to produce these higher value products can have a significant impact on the global crop demand. Key drivers of per capita demand are commodity prices and per capita incomes. The changes in these drivers are then mediated by the price and income elasticities. Per capita consumption is coupled with population to derived regional consumption.

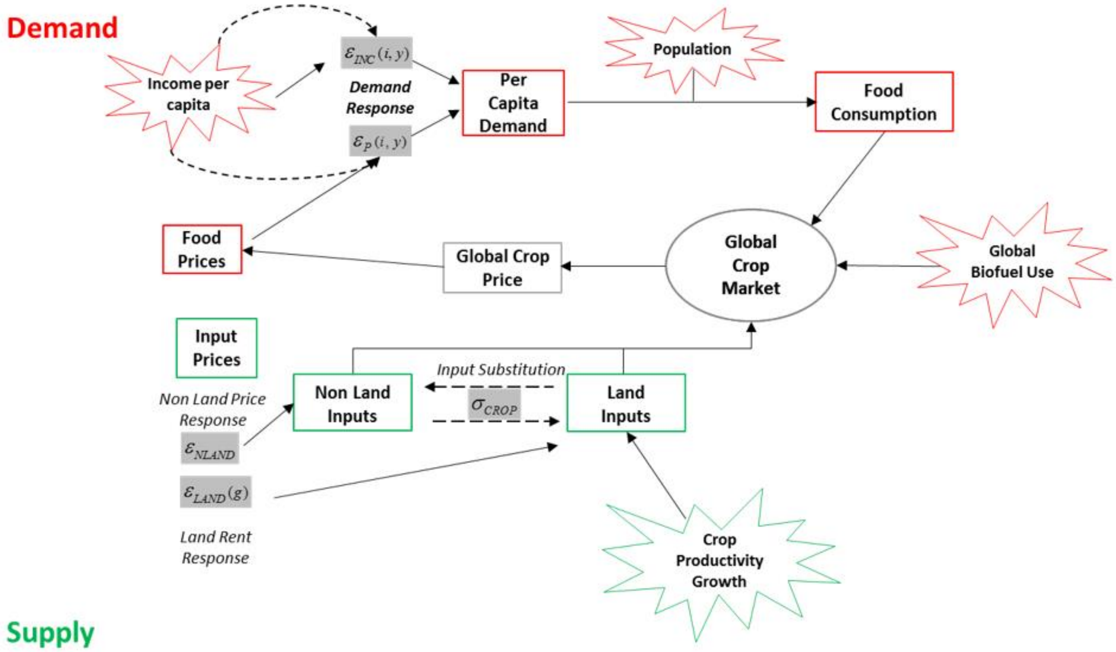

Figure 3.1: Overview of SIMPLE

The implications of rising income levels for long-term consumption patterns are well documented (Aiking et al., 2006; Foresight, 2011; Frazão, Meade, & Regmi, 2008; Tweeten & Thompson, 2009). As income increases, consumers tend to shift from a diet high in carbohydrates (e.g., from staple crops) to one which is rich in protein (meats and dairy products). In addition, the share of households' expenditures devoted to food declines while this share increases for non-food commodities – a phenomenon commonly referred to as Engel's Law. Since income growth is an extremely important part of any long run scenario, it is imperative to incorporate this upgrading process into the model. As detailed in the next section, this is done by allowing the income and price elasticities for each commodity to vary with changes in incomes using linear regression estimates between per capita incomes and these demand elasticities.

Total demand for crops in the model consists of the regional direct demand for crops, regional derived demands for crops as feed for livestock, and as raw material inputs for processed food production, as well as global demand for feedstocks in biofuel production. As with the theoretical model of Hertel (2011), there is a single, global market clearing condition for crop products in SIMPLE. With global supply required to equal global demand for crops, the equilibrating variable in the model is the global price for crops. The global supply of crops is the summation of production across regions, each of which is characterized by differing land endowments and productivity.

Production in the model uses the constant elasticity of substitution (CES) framework. In each region, the production of crops requires the use of two aggregate inputs namely land and non-land. Substitution possibilities between these inputs are governed by the elasticity of substitution. The larger this value, the greater the intensive margin of supply response which in turn dampens cropland expansion. The supply of cropland, and hence the extensive margin of supply response, is a function of land rent in each region as translated through the land supply elasticity.

The main departure from the model of Hertel (2011) is the assumption that the supply of non-land inputs is perfectly elastic. Instead, as with land, there is a finite elasticity of supply for non-land inputs which means that the price of these inputs rise in response to increased input demand. This is in recognition of the empirical fact that other inputs, in particular farm labor, are often inelastically supplied to agriculture – albeit with a greater supply response than land (Salhofer, 2000).

Production and consumption of livestock and processed food products are assumed to clear within a region; hence prices for these composite food commodities can vary by region. Following the crop sector, production of livestock follows the CES framework while for processed foods, Leontief production is assumed (i.e. fixed proportions production). These sectors use two composite inputs namely crop and non-crops inputs. In the case of livestock products, it is assumed that cheaper crop inputs may result in more intensive use of feedstuffs, per unit of livestock output.

3.3: Model Database and Parameters

To implement the model, a global database for the year 2001 is constructed. A total of 119 countries are grouped by income into 5 demand regions while on the supply side, 7 geographic regions are identified[3]. The income groupings outlined in the World Development Indicators (2003) is used. This is based on 2001 per capita gross national incomes[4]. This classification results in 5 income categories namely low income category (including India), and two middle income categories (lower middle includes China while upper middle includes countries like Brazil), along with two high income categories.

Data from external sources include income, population, consumption expenditures and crop production and their sources are as follows. Information on GDP in constant 2000 USD and population are obtained from the World Development Indicators (2011) and from the World Population Prospects (2011), respectively. Consumption expenditure

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[3] A more recent version of SIMPLE covers 154 countries which are aggregated to 15 geographic regions. The coverage of crops is also extended from 50 to 135 crops.

[4] The income classifications are the following: $745 or less are low income, $746 to $2,975 are lower middle income, $2,976 to $9,205 are upper middle income and, $9,206 or more are high income. In addition, we define upper (lower) high income countries as high income countries which are OECD (Non-OECD) members.

data is taken from the GTAP V.6 database (2006) – which was constructed under reference year 2001 – while data on cropland cover and production, utilization and prices of crops are derived from FAOSTAT (2013). Around 50 crops are considered including grains such as corn, rice, sorghum and oilseeds such as soybeans and rapeseeds. In SIMPLE, cropland is based on arable land and permanent croplands.

The data above is then combined with additional information on industry cost and sales shares in order to construct the rest of the database. This is calculated from the crop price and quantity information. On the other hand, data on crop quantities require further processing. Note that quantities are aggregated from different crops with varying economic values so comparison of crop quantities (and crop yields) across geographic regions is not straightforward. Given this issue, it is necessary to account for the economic contribution of each crop while still preserving its physical quantities. Following Hayami and Ruttan (1985), crop quantities are converted into corn-equivalent quantities using weights constructed from world crop prices and the world price of corn[5]. The normalized quantities are then allocated across uses. The amount of crop feedstock used by the global biofuel sector using the sales shares by the global crop sector are taken from GTAPBIO V.6 (Taheripour, Birur, Hertel, & Tyner, 2007). Shares constructed from the crop utilization data are then used to split the remaining crop quantities across each income region and across different uses (i.e. food, feed and raw materials for processed food). The global crop price is calculated from the value of crop production and the normalized quantity data. The global price and the allocated quantities are used to derive the value of crop input use in the livestock and processed food industries. Under the

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[5] The world price for each crop is simply computed from the country-level crop price and quantity data. We then used the average world price from 2004 to 2008 to construct the required price weights

assumption of zero profits, total value of land and non-land input costs in the regional crop sectors are calculated using GTAP v.6 cost shares as a guide. GTAP data base is also used as a guide in classifying each geographic region according to the value of the cost share of land input (high, medium, low). Each category has its own corresponding land cost share (26.0%, 18.0% and 9.0%, respectively). Regions which have high land cost share include Europe & Central Asia and North America while those which have low land cost share, and relatively abundant land, consist of Latin America & Caribbean and Sub-Saharan Africa. GTAP v.6 cost shares and the value of crop input usage in the livestock and process food industries are again used to impute the value of non-crop inputs in these sectors. Finally, land rents and crop yields for each geographic region are derived using the value of land inputs, crop production and cropland areas. Details regarding the values of the model variables are summarized in Appendix C.

Parameters which guide consumption and production behavior in SIMPLE are taken from several sources. Demand elasticities in the model consist of income and price elasticities for each commodity aggregate (i.e. crops, livestock, processed foods and non-food).These are based on the country-level estimates by Muhammad et al (2011). The authors examined international consumption patterns for 144 countries using 2005 expenditure data from the International Comparison Program. The authors then estimated demand elasticities for commodity aggregates (via the Florida-Preference Independence model) and for food subcategories (via the Florida-Slutsky model). Estimates of the unconditional Frisch own-price and expenditure elasticities for food subcategories are implicitly used in SIMPLE via linear regressions of these demand elasticities on per capita incomes. The predicted income elasticities capture the implications of dietary upgrading. Within a region, the income elasticity of demand for livestock and processed foods are always higher than for crops. This implies that a larger fraction of additional income is spent on livestock and processed food rather than on food crops. However, all of the food commodities have income elasticities of demand less than one so that the budget share of food will fall with rising incomes.

Production parameters in SIMPLE include: the elasticity of substitution between land and non-land inputs in crop production and the price elasticity of non-land input supply – both derived from Keeney and Hertel (2005) – and the 5-year and 15-year price elasticities of U.S. land supply which are taken from Ahmed, Hertel and Lubowski (2008). The regional elasticities of land supply from Gurgel, Reilly and Paltsev (2007) are also used. These are adjusted and calibrated for the 5-year and 15-year periods using the values for the U.S. as the guide (i.e. regional variation is taken from Gurgel et al and the level of the 5 and 15 year U.S. elasticities are taken from Ahmed et al.). Note that the 5-year elasticities are used during model calibration over a 5 year historical period, while the 15-year elasticities are used in long-run experiments for 15 years or more. The global supply elasticity of non-land inputs is scaled up for long-run experiments using the ratio of the 5-year and 15-year land supply elasticity as a guide. Appendix D summarizes the parameters used in the SIMPLE model.

The land supply elasticities reflect the relative scarcity of new croplands across geographic regions. From Appendix D, it is obvious that regions wherein additional croplands are relatively abundant include Latin America & the Caribbean and Sub-Saharan Africa while new croplands are relatively scarce in North America, East Asia & Pacific, and Europe & Central Asia. Also, note that the supply elasticity for non-land inputs is greater than for land since it reflects the composite supply of labor, capital and purchased materials which are generally more price elastic than land. The supply elasticities for both these inputs also become more elastic in the long run.

3.4: Model Tuning

As with any global model, some tuning is necessary in order to ensure reasonable performance of the integrated, equilibrium model. However, the model is tuned over the short run period 2001-2006 rather than the full period for which the historical validation is undertaken (i.e. 1961-2006). Demand shocks includes population, per capita incomes and global biofuel demand which are taken from the UN World Population Prospects (2013), World Development Indicators (2013) and International Energy Agency (2008, 2012), respectively. Exogenous assumption on technical changes in the crop, livestock and processed food sectors are based on the total factor productivity (TFP) growth rates from Fuglie (2012), Ludena et al (2007) and Griffith et al (2004), respectively. The model is tuned on three key dimensions of global agriculture. First, the economic yield response to crop price is calibrated such that it matches that from the literature in the short-run (Keeney & Hertel, 2008). Specifically, a 1% increase in global crop price translates to a 0.25% increase in crop yields. Second, the unobserved intensification parameters in the livestock and food processing sectors are calibrated due to lack of robust estimates for these parameters. For the livestock sector, this parameter is calibrated by focusing on the high income region, which is deemed to be most representative of future developments in the livestock industry, and select the parameter which best fits the data on feed input use for this region, over this period. This value is subsequently assigned to all demand regions. For the processed food sector, the elasticity of substitution between crop inputs and non-crop inputs for the processed food sectors is set to zero under the assumption that this relationship is fixed over time (i.e. Leontief production). Finally, the regression estimates of the income and price elasticities are adjusted by re-estimating the linear regressions of the demand elasticities with per capita incomes using deflated per capita incomes (divided by a factor of 4). In the initial calibration effort, the simulated change in global crop demand for food (10.9%) is nearly one-quarter greater than the historical change (around 8.8%). This adjustment closes this gap by dampening the magnitude of the regression intercepts while maintaining the values of the regression slopes.

SIMPLE is implemented using the GEMPACK program (Harrison & Pearson, 1996) 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. This subtotals feature is used in this chapter and in Chapter 4 to decompose the contribution of each model driver on the changes in key variables.

3.5: Model Validation

Since the SIMPLE model is designed to make forward looking projections from 2006 to 2050 (see Chapter 4), the model is evaluated over a comparable period of time – in this case from 1961 to 2006[6]. The most obvious metrics involve comparing

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[6] One issue which must be confronted in such a validation exercise is whether to report the results going backwards in time, or going forward. In this study, the model is first simulated backwards to 1961,

endogenous predictions to observed changes in the following global scale variables: (a) crop production, (b) crop price, (c) cropland area, and (d) average crop yield. To derive these endogenous changes in SIMPLE, the model is perturbed using the main exogenous drivers of global agriculture during this historical period, including: population and per capita income (by demand region) and total factor productivity (TFP) for crops (by supply region), livestock and food processing (by demand region). The values for these exogenous drivers are reported in Table 3.1. Looking at the table, population and per capita incomes grew steadily during this historical period. Notable growth in population can be observed in the lower high, upper middle (such as Brazil) and low income regions (such as India). Likewise, steady growth in per capita incomes is observed with the lower middle income region (including China) showing sharply higher per capita income growth (4.3% per annum). Crop supplies are mainly driven by the growth in TFP which is the key measure of productivity improvement in the model. For the crop sector, TFP grew by more than 1.2% per annum, with the exception of Sub-Saharan Africa where it grew by 0.9% annually. With regard to the livestock sector, strong TFP growth in the lower middle income region is observed. In contrast, livestock TFP growth in the low income region grew by only 0.2% per annum. Due to lack of reliable regional estimates, a uniform rate in the TFP growth in the processed food sector is imposed across all regions.

Global validation results are reported in Figure 3.2. Based on the figure, SIMPLE slightly overstates the global change in crop production over the 1961-2006 period (204% vs. 196%). The model also understates the historical decline in crop price (25% vs. 29%).

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thereupon establishing an historical equilibrium. In the validation experiment, the model is then simulated again forward to 2006, comparing these results to the observed changes over this period.

Table 3.1: Growth Rates for Key Exogenous Variables: 1961-2006

Income Regions	Population	Per Capita Income	TFP: Livestock			Geographic Regions
			Livestock	Processed Food	Crops	
Up Higher	0.79	2.62	0.92	0.89	1.89	East Asia & Pacific
					1.78	Europe & Central Asia
Low Higher	2.64	2.69	0.92			
					1.58	Latin America & the Caribbean
Up Middle	2.07	1.71	0.75		2.19	Middle East & North Africa
					1.65	North America
Low Middle	1.71	4.25	2.20			
					1.15	South Asia
Low	2.26	2.35	0.16			
					0.91	Sub-saharan Africa

Sources: From left to right – UN World Population Prospects (2013), World Bank Development Indicators (2013), Ludena et al. (2007), Griffith et al. (2004) and Fuglie et al (2012)

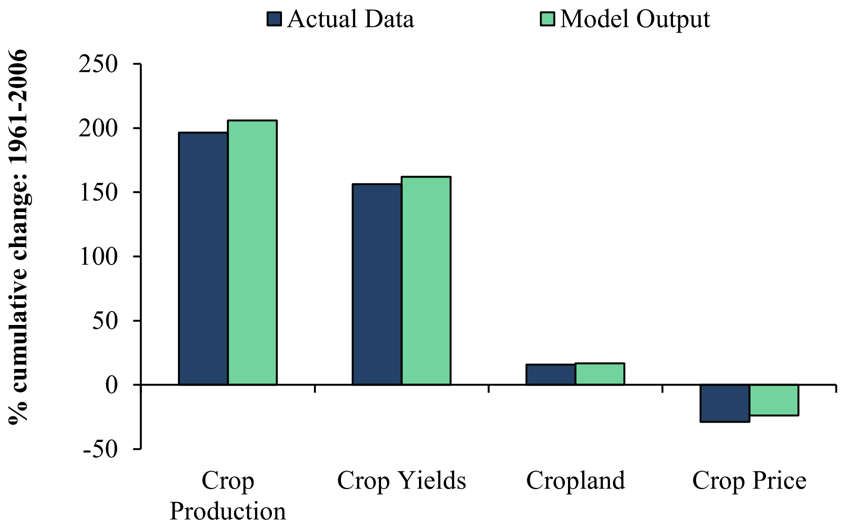


Figure 3.2: Validating Historical Changes at the Global Level: 1961-2006

SIMPLE does a very good job in predicting the partitioning of supply growth between the intensive and extensive margins, with changes in global cropland and global average crop yield (16% and 161%, respectively) slightly above the observed values (16% and 156%, respectively) due to the higher level of global output. Overall, these global results are remarkable and encouraging since it demonstrates that SIMPLE incorporates the key drivers and economic responses that govern long-run changes in agriculture, at the global scale. These global results are revisited again when discussing the implications of assumptions embedded in agricultural models currently in use.

The decomposition of the historical changes in global crop production, average yields, crop land and price are illustrated in Figure 3.3. The decomposition is useful in ranking which driver has the largest contribution to total changes in key model variables. Looking at the figure, it is population – and not income – which is the main driver of historical growth in crop demand. Given this, its impact on crop production (in red) is also significant. Population is then followed by total factor productivity (in green). TFP is an important source of yield growth and it helped dampen crop land use expansion during this period. More importantly, the TFP growth is key to the historical reduction in food prices. The linkages between TFP growth, food prices and food security are discussed in-depth in the next chapter of this dissertation.

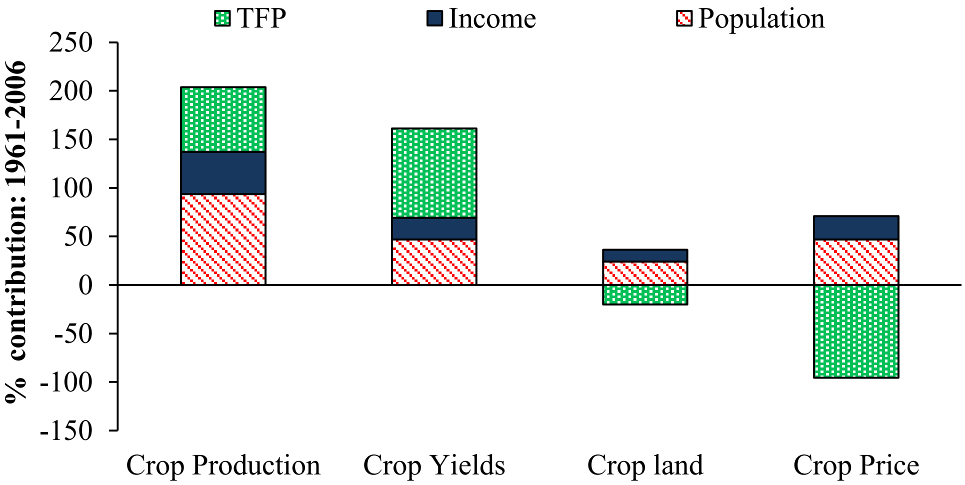
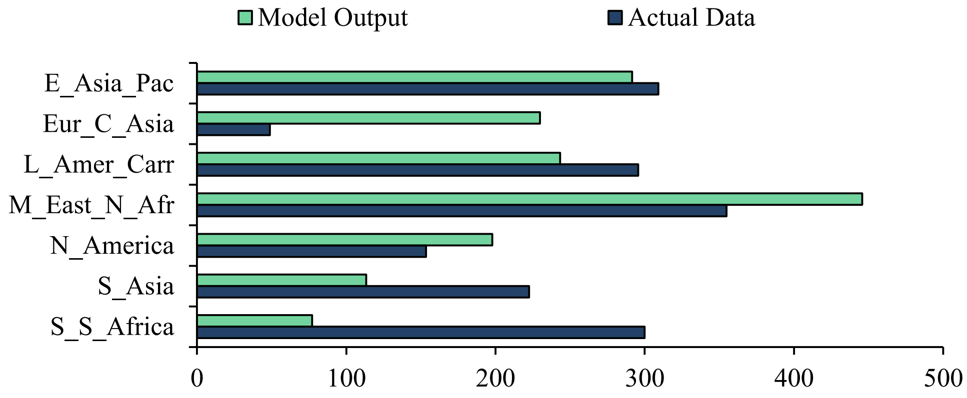
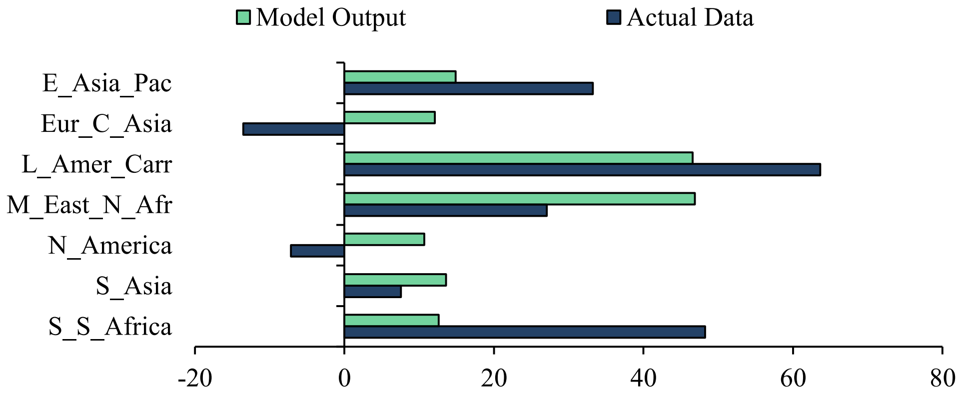


Figure 3.3: Decomposing the Historical Changes at the Global Level: 1961-2006

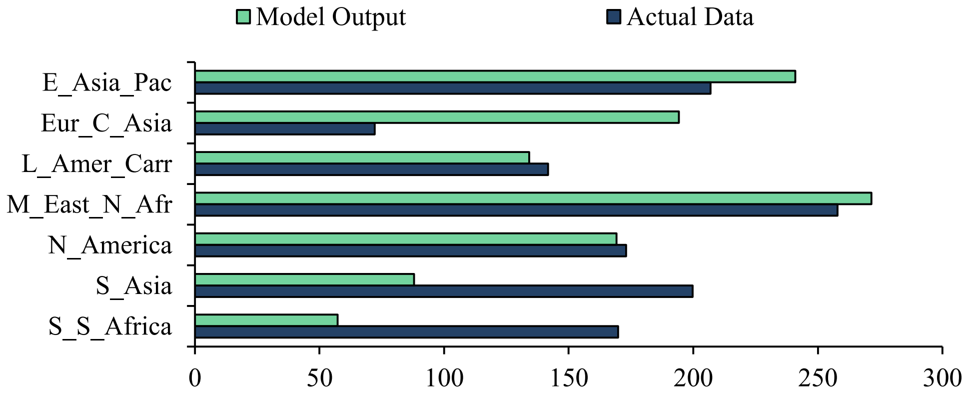
Before proceeding further, however, it is important to note that the regional results on cropland and production are much less satisfactory than the global results (Figure 3.4), with too little area expansion in East Asia & Pacific, Latin America & Caribbean and Sub-Saharan Africa, and too much expansion in other regions. Indeed, SIMPLE is unable to capture the reduction in cropland area in North America and Europe. However, these results are consistent with the literature. Other agricultural models also find it difficult to capture changes at the regional levels (McCalla & Revoredo, 2001). By moving from global to regional projections, it is obvious that regional drivers become more important. In the case of SIMPLE, the discrepancies in the regional results can be attributed to the absence of domestic agricultural and foreign trade



% cumulative change in crop production : 1961-2006



% cumulative change in crop lands : 1961-2006



% cumulative change in crop yields : 1961-2006

Figure 3.4: Validating Historical Changes at the Regional Level: 1961-2006

policies, as well as the fact that the model ignores other barriers to trade, including poor infrastructure and administrative obstacles. Fundamental to SIMPLE’s allocation of global production across regions is the assumption of fully integrated global crop markets. Yet this was far from the truth throughout most of the historical period. This state of affairs was highlighted by D. Gale Johnson who published a series of papers and books on the topic of “World Agriculture in Disarray” (Johnson, 1973) over the post WWII period. In this work, Johnson discusses the many distortions which caused the global distribution of agricultural output to be inconsistent with economic logic. The evolution of these distortions has subsequently been documented in a path-breaking study by Kym Anderson (2009). Since the completion of the Uruguay Round of talks, which resulted in establishment of the World Trade Organization, agricultural support has been reformed in many parts of the world. However, there remain significant barriers to free trade in agricultural products (Anderson & Martin, 2005) and this suggests the need to incorporate such policies into SIMPLE if it is to accurately reflect the regional evolution of future production.

In addition to explicit government policies shaping the regional patterns of agricultural production, there are other important barriers to international trade in agricultural products, including poor quality domestic transport infrastructure, burdensome customs procedures and poorly developed port facilities. These barriers to trade loom particularly large in Sub Saharan Africa (Wilson, Mann, & Otsuki, 2004), and have limited that regions’ engagement in the global trading system. As a consequence of this insulation from world markets, Sub Saharan Africa’s output has grown much more than would have been anticipated, given its relatively low rate of productivity growth over the 1961-2006 period. And its increased output has largely been directed to domestic consumption. This is reflected in the fact that its share in global trade of agricultural products has declined by around 70% during this historical period (FAO, 2013).

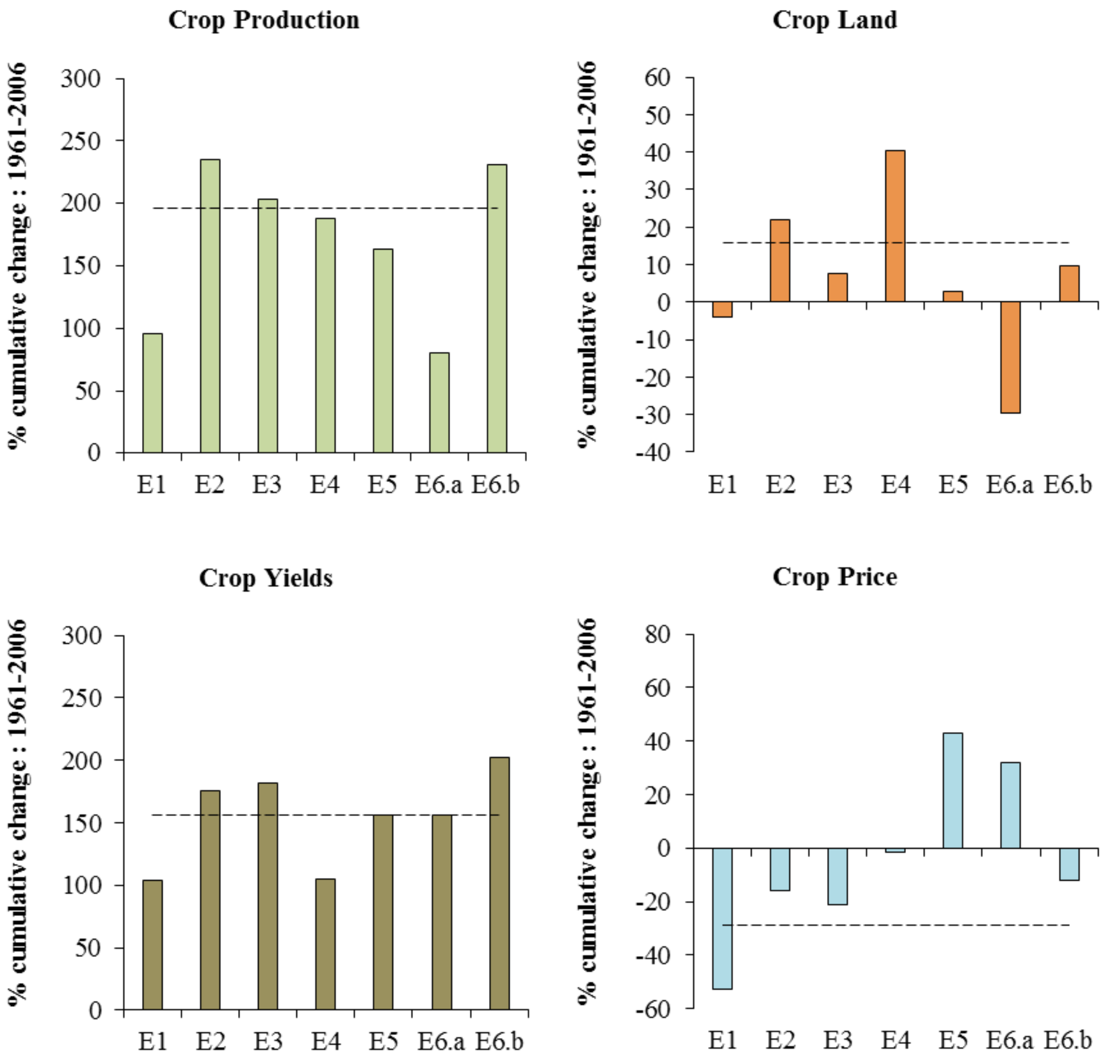
In summary, the results of the validation experiment suggests that, while SIMPLE is adept at capturing long run changes in output and land use at global scale, the problem of allocating these changes across regions is far more challenging. In light of these findings, the analysis in the next section is restricted to global scale variables.

3.6: Evaluating Key Assumptions in Other Global Models

Existing global agricultural models produce significantly different projections of global land use in 2050 (Schmitz et al., 2014; Smith et al., 2010). This is hardly surprising, given the widely varying assumptions imbedded in the models. Some of these differences may be inconsequential for simulating global land use change, while others may be critically important. Absent a laboratory in which to test these alternative assumptions it is impossible to know which model results are reliable. For this reason, it would be invaluable to have a standard set of validation experiments against which to evaluate model performance, test new features, and set future research priorities.

In this section, a set of experiments is introduced, each focusing on a specific restriction to the SIMPLE model, aimed at highlighting the consequences of each assumption for global land use change. These restrictions have been chosen to highlight shortcomings in existing global models and assess their relative significance. They include: exogenous per capita food consumption (E1), fixed price and income elasticities of demand for food (E2), short- to medium run input supply elasticities (E3), the absence of endogenous intensification of crop production (E4) and historical trend-based yield projections (E5). To illustrate the potential for interactions amongst these restrictions, two experiments (E6.a and E6.b) are considered which include multiple elements of the earlier experiments designed to reflect combinations of assumptions sometimes found in biophysical and in economic models of global agricultural land use.

Figure 3.5 summarizes the results from these restricted experiments. In every case, the key historical drivers of change: population, income and total factor productivity growth, are identical to the historical baseline. A good starting point is the restrictions in the way crop demand is modeled given the simplest possible assumption, namely exogenizing per capita food consumption as is done in some versions of agricultural models with limited consumer demand systems (Wise et al., 2009). As illustrated in Figure 3.5, preserving the historical per capita food consumption (E1) leads to an understatement of the increase in global crop demand and global crop production over this historical period. With less output growth, but the same level of TFP growth, prices fall sharply, yields grow more slowly, and global cropland use contracts. A more common consumption specification in global agricultural models is to have fixed (unchanging) price and income elasticities of food demand (Havlik et al., 2013; G. Nelson et al., 2010). In this case, rather than becoming smaller in absolute value as per capita incomes rise (recall Figure 3.1) (Muhammad et al., 2011), the responsiveness of demand to rising incomes is based on historical estimates of these values and is kept constant (E2). Figure 3.4 clearly illustrate that under this scenario both global crop demand and global crop production are overstated. This is due to the dominance of the income effect over this projections period. With sharply rising incomes, a failure to



Crop Production

Crop Land

Crop Yields

Crop Price

Figure 3.5: Impact of Restrictions on the Historical Changes at the Global Level: 1961-2006

account for the diminishing impact of marginal increments to purchasing power results in excessively high demand and a significant overstatement of historical production, area and yield, while global crop price falls by only about half of its observed value.

Looking at the supply side of the global agricultural picture – recall that there are two key margins of economic response here: the extensive margin (additional area) and the intensive margin (yield increases). Starting with the parameters which influence the extensive margin, in scenario E3 the long-run supply elasticities for land and non-land inputs are replaced with their corresponding short-run (five year) values from the 2001-2006 tuning exercise. Models which are based on econometric estimates of cropland area response are likely to fall prey to this limitation (Golub et al., 2012; G. Nelson et al., 2010). This is because such estimates are typically based on annual time series data from which it is hard to extract long term supply response. This point is emphasized by Hertel (2011) who offers indirect evidence that prominent global studies of biofuels (Fischer, Hizsnyik, Prieler, Shah, & Velthuizen, 2009) and climate impacts (G. Nelson et al., 2010) are likely not using long run elasticities in their models. With these short-run parameters in place, the results in E3 show how a smaller global supply response leads to a rise in crop prices over this period, as cropland area is unable to respond as vigorously to increased land demand for crop production. While yield changes are comparable to their historical values over this period, production falls short of its historical value, despite the rising crop prices.

The other critical component of supply is the response of yields to higher crop prices and/or increased scarcity of land. While the size of this response is hotly debated (Berry & Schlenker, 2011; Goodwin, Marra, Piggott, & Mueller, 2012; Huang & Khanna, 2010; Keeney & Hertel, 2009), there is little doubt that significantly higher prices do encourage farmers to respond with more intensive cultivation practices. Yet not all agricultural models incorporate this possibility (Calvin, Wise, Page, & Chini, 2012), and it is often unclear how large this effect is in those models that do allow for endogenous yield response (Havlik et al., 2013; Lotze-Campen et al., 2008; G. Nelson et al., 2010). This issue is further explored in experiment E4 wherein this intensive margin of supply response is eliminated. As a consequence, yields grow more slowly than in the historical record – being driven solely by TFP growth. Crop prices are essentially flat and cropland expansion is in excess of 40% – as opposed to the observe change of just 16%. Clearly failure to account for the intensive margin of supply response can be expected to lead to a significant overstatement of future cropland requirements.

A slightly different approach involves explicitly targeting the rate of average crop yield growth (as opposed to targeting TFP). This is relevant, since many biophysically-based agricultural models treat productivity growth as arising largely through crop yield improvements (Havlik et al., 2013; Lotze-Campen et al., 2008; G. Nelson et al., 2010). Of course, if the growth rate of crop yields in the future yield is known, one can expect that it would help greatly in making credible projections of global land use change. But, as experiment E5 demonstrates, even knowing yields with certainty does not result in accurate prediction of cropland change over this historical period. Since land is only one of many agricultural inputs, accurately projecting yields does not allow for an accurate prediction of the change in crop prices over time, as can be seen from the bar for E5 in the lower right panel in Figure 3.5. This in turn leads to the underestimation of the changes in crop production and cropland use.

The last two experiments illustrate the potential impacts in the historical projections when some of the above restrictions are combined. A good starting point is a purely biophysical view of the historical period wherein per capita food consumption is exogenous, the crop yield response to higher crop prices is absent (i.e. no intensive margin) and crop yield growth is targeted (E6.a). Similar to the first experiment, global crop production in this scenario is grossly understated (upper left panel of Figure 3.5). By targeting average yields and ignoring the economic yield response, the changes in global cropland use and global crop price move in the opposite direction of what was observed over this historical period.

Another interesting combination of restrictions is captured by E6.b, which seeks to mimic the behavior of those global agricultural models which fail to account for long run changes on the demand and supply sides. Specifically, the price and income elasticities of demand for food do not evolve with per capita incomes in this scenario. In addition, the short to medium run input supply elasticities are imposed. With an overly responsive demand for food, the projections tend to capture the rise in global crop production but erroneously predict the change in global crop price. As the supply of land is less responsive to land rents, global crop demand can only be met by increasing the use of non-land inputs; hence, global average crop yields are overstated while global cropland expansion is understated under this scenario.

3.7: Summary and Conclusions

This chapter illustrates an approach to validating agricultural land use in global models by looking back at the historical experience from 1961 to 2006. Using the SIMPLE model, the historical changes in global crop production, cropland use, average crop yield and crop price are successfully replicated using only population, incomes and total factor productivity as the key drivers of agriculture. However, the model performs relatively poorly in the geographic distribution of production and land use changes over this period which suggest that there regional drivers and market barriers which are not captured in SIMPLE. Addressing these limitations requires further research and refinement of the framework and some of these ideas are discussed in the last chapter of this dissertation. In the meantime, there is still great value in testing existing agricultural models at global scale and comparing predicted changes in production, land use and crop prices to observed values.

It is important to highlight how critical assumptions within existing agricultural models alter global outcomes and SIMPLE can serve as a laboratory to conduct such experiments. Scientists who use such models for long-run projections should be aware of the implications of these assumptions. As explored in this chapter, those models which are largely biophysical – and ignore the price responsiveness of demand and supply – likely understate changes in crop production, while failing to capture the changes in cropland use and crop price. On the other hand, those models which incorporate economic responses based on statistical estimation of key parameters using limited time series estimates likely understate long run supply and demand responses to crop price. By imposing short-run assumptions on SIMPLE over the 45 year test period, the model tends to over-predict historical output changes, while understating land use change. By testing each global agricultural model against the historical record, researchers can better understand where their models succeed or fall short which will greatly help in prioritizing areas for model improvement.

Successful validation of SIMPLE over the long-run historical period helps build confidence in using the model to make forward-looking projections. And as evidenced in the historical assessment, trends in TFP growth will most likely influence the evolution of global agriculture in the coming decades. Going forward to 2050, sustained productivity growth can also help achieve food security targets through the reduction in food prices.

However, the SIMPLE model developed in this chapter is not yet equipped to properly tackle the assessment of future food security outcomes. In the next chapter, a food security module was developed and is used to examine the changes in nutritional attainment by 2050 given expected trends in TFP growth and uncertainties posed by climate changes on agricultural productivity.

CHAPTER 4. GLOBAL FOOD SECURITY IN 2050: THE ROLE OF AGRICULTURAL PRODUCTIVITY AND CLIMATE CHANGE [7]

4.1: Background and Motivation

In the coming decades, greater per capita food consumption is expected in the wake of growing incomes in the developing world. The resulting shifts in consumption patterns from a diet high in starchy foods to one that is richer in protein, including meats and dairy products (Gerbens-Leenes et al., 2010) will have an important impact on the shape of global agriculture. Shifts in the types of foods consumed, from local towards Western foods, are also expected (Pingali, 2007). Given these trends, the existing competition for crop output between direct consumption, and livestock feedstuffs, and raw inputs to processed food industries will intensify. At the same time, the industrial demand for crops is expected to rise with the growing use of renewable fuels worldwide, especially for first generation biofuels which require crop feedstocks (Fischer et al., 2009).

Over the past five decades, food availability has been greatly enhanced through productivity gains in the agricultural sector. Continuation of such trends will be critical to ensuring food security between now and mid-century, as population, incomes and biofuel use continue to grow. Total factor productivity – a measure of the growth in aggregate

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[7] This chapter draws from the article by Baldos, U. L. C., & Hertel, T. W. (2014). Global food security in 2050: the role of agricultural productivity and climate change. Australian Journal of Agricultural and Resource Economics doi:10.1111/1467-8489.12048

output relative to an index of all inputs – in both the global crop and livestock sectors – has actually sped up over the past two decades (Fuglie, 2012; Ludena et al., 2007). However, there are concerns that crop yields for key staple foods may be reaching their biophysical limits in some regions (Alston et al., 2009). This could have an adverse effect on global food availability and prices. The future trajectory of crop yields will also be affected by climate change, although the precise impacts are uncertain and spatially heterogeneous. Depending on location, the temperature and precipitation impacts of climate change may cause crop yields to rise or fall (Tubiello et al., 2007). There is also the potential for crop yields to be enhanced via the fertilization effect of rising CO_2 concentrations in the atmosphere (David B. Lobell & Field, 2008).

This chapter examines how global food security in 2050 will be affected by the trends in agricultural productivity and the complexities introduced by climate change. It adds to the existing literature which examines long-run global food security issues. These studies are based on a variety of methods, including: expert opinion coupled with trend analysis (Alexandratos & Bruinsma, 2012), integrated assessment models (Fischer, Shah, N. Tubiello, & van Velhuizen, 2005; Schneider et al., 2011; Tubiello et al., 2007) and partial as well as general equilibrium economic models (Golub et al., 2012; Msangi, Ewing, & Rosegrant, 2010; G. C. Nelson et al., 2013; G. Nelson et al., 2010). However, most of these studies use limited metrics of food security which only encompass average changes in per capita dietary energy consumption (DEC) in each region, whereas it is really the *distribution of caloric consumption* across the population that is most critical for food security. In addition, these studies are largely based on models which have not been validated against the past. By looking at the past prior to projecting into the future, insights can be gained regarding the potential changes in the relative importance of each major driver of global food security, as well as boosting confidence in the resultant projections.

In light of the existing literature, this chapter makes three contributions. First, it outlines how to quantify not only the prevalence of food insecurity given the drivers of the global farm and food system, but also the average depth of such insecurity, by accounting for the full distribution of dietary outcomes in each region. Second, food security outcomes are validated against historical changes to assess how well the model replicates observed changes in malnutrition outcomes. Third, decomposition of the historical and projected drivers of food security is implemented in order to assess the relative importance of each major driver, with emphasis on the contribution of agricultural productivity and climate change by 2050

The rest of this chapter is organized as follows. Section 4.2 starts with a brief discussion of the SIMPLE model of global agriculture and then continues with the food security module which has been specifically developed to extrapolate nutritional outcomes from the changes in average food consumption. In Sections 4.3 and 4.4, all the experiments in this chapter are outlined. To evaluate the model and see how well it predicts food security metrics, the model is validated against the historical period 1991 to 2001 (Section 4.3). Going forward, a series of projections from 2006 to 2050 are implemented and these are documented in Section 4.4. These future scenarios are designed to help understand the implications of agricultural demand and supply drivers on future nutritional outcomes. The results are discussed in Section 4.5 while the final section offers a summary and some concluding remarks.

4.2: Food Security Outcomes in SIMPLE

To project the broad changes in the global farm and food system over the period 2006 to 2050, the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE) is used (U. L. C. Baldos & Hertel, 2013). It is a partial equilibrium model but unlike other global models, which are highly disaggregated, SIMPLE is designed to be as parsimonious as possible, while faithfully producing estimates of crop demand and supply at a global scale. The model has been used in studies focusing on climate change mitigation and adaptation (Lobell *et al*. 2013) as well as model validation and evaluation (U. L. C. Baldos & Hertel, 2013). In the latter study, it is shown to do remarkably well at capturing observed global changes in crop production, area, yield and price over the period: 1961-2006 (see Chapter 3, for further discussion of SIMPLE). For this chapter, a disaggregated version of the model was developed to assess nutritional outcomes for the 15 geographic regions (Appendix E).

To extract information on nutritional outcomes from SIMPLE, a food security module was developed. It has two main functions. First, it characterizes the distribution of dietary energy consumption within each region, which allows the calculation of the incidence, headcount and average depth of malnutrition. Second, it links the food caloric content to per capita income which captures the shifts in the composition of food, as well as the presence of food waste, within the broad categories of crops, livestock and processed foods. Linear regressions are used to estimate the relationships between the log of per capita income and the food caloric content of each commodity and these are illustrated in Figure 4.1. The figure shows a negative relationship between the caloric content of from raw products for consumption of crops and processed food while there is a small rise in caloric content from livestock as incomes rise. Lastly, the module relates changes in the average per capita DEC to shifts in its distribution and to corresponding changes in the incidence, headcount and average depth of caloric malnutrition for each region.

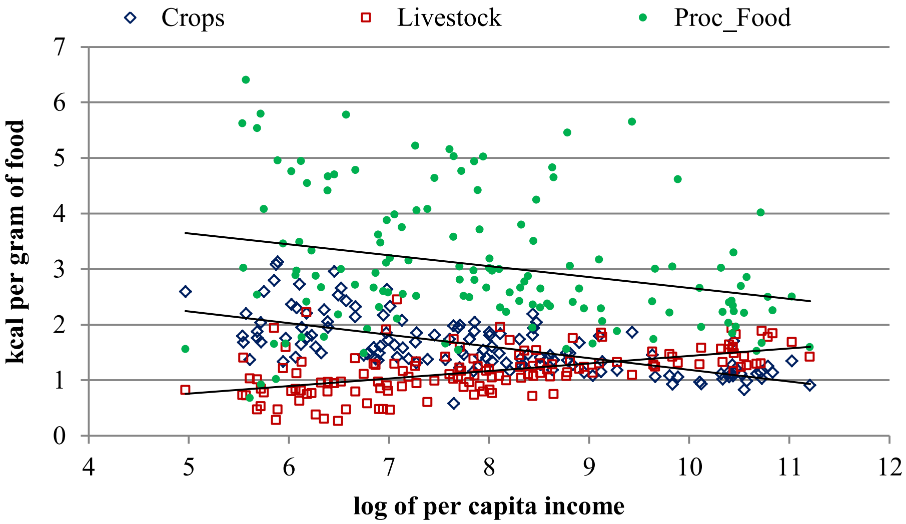

Figure 4.1: Scatterplot of Food Caloric Content and Log of Per Capita Income

Two key measures of food security used in this study include the malnutrition incidence and the malnutrition gap. The former measures the prevalence of undernourishment by reporting the fraction of population whose daily dietary energy intake is below the minimum requirement. The latter captures the intensity of food deprivation which is the average dietary energy deficit that an undernourished person needs to close in order to satisfy the minimum requirement (FAO, 2012). In the literature, it is common to focus on the changes in malnutrition incidence (Alexandratos & Bruinsma, 2012; Alexandratos, 2010). However, this measure ignores the variations in dietary energy deficits faced by malnourished persons. By reporting the malnutrition gap, changes in the average depth of food insecurity within a region can be examined.

Mathematically, the malnutrition index and gap are equivalent to the poverty index and gap measures as proposed by Foster, Greer and Thorbecke (1984). Given this, it is possible to apply the concept of poverty-growth elasticities to link these measures to the average per capita dietary energy intake. Widely used in the poverty literature, these growth elasticities measure the percent changes in the indices of poverty and poverty gap given a one percent change in average per capita income (Bourguignon, 2003; Lopez & Serven, 2006). To apply this concept in the case of dietary energy, it is required to assume that the distribution of per capita dietary energy consumption is lognormal. This is consistent with the traditional assumption used by FAO regarding the distribution of dietary energy intake within a country (Neiken, 2003). The following equations are used to calculate the growth elasticities for the malnutrition index (ε_{MI}) and malnutrition gap index (ε_{MGI}). They characterize the % change in these indices in the wake of a one percent rise in income:

$$\varepsilon_{MI} = -\frac{1}{\sigma}\frac{\tau}{\pi}\left[\frac{\ln(w/y)}{\sigma} + \frac{\sigma}{2}\right] \tag{1}$$

$$\varepsilon_{MGI} = -\frac{\pi\left[\ln(w/y)/\sigma - \sigma/2\right]}{(w/y)\pi\left[\ln(w/y)/\sigma + \sigma/2\right] - \pi\left[\ln(w/y)/\sigma - \sigma/2\right]} \tag{2}$$

In these equations, w is the minimum daily energy requirement (MDER), y is the average per capita DEC, and σ is the standard deviation of the DEC distribution. The operators: τ and π denote the standard normal probability density and cumulative distribution functions, respectively.

The malnutrition gap is calculated from the product of the minimum energy requirement and ratio of the malnutrition gap index and the malnutrition index. The updated malnutrition headcount is then calculated from the product of the new malnutrition index and population headcount.

Figure 4.2 illustrates how the distribution of per capita dietary energy intake evolves given the changes in average dietary energy consumption. Specifically, it shows the probability densities of per capita DEC in 2006 (solid line), obtained from published food security data (FAO, 2010, 2012), and in 2050 (dashed line), based on the baseline scenario, for both South Asia and Australia/New Zealand. The vertical solid line within each distribution represents the minimum dietary energy requirement. The area to the left of this line is the fraction of the population which is malnourished, having dietary energy intake below the MDER. Note that the DEC distribution is much more compact for Australia/New Zealand than for South Asia, suggesting a more equitable distribution of dietary energy. Under this framework, as the distribution of dietary energy intake

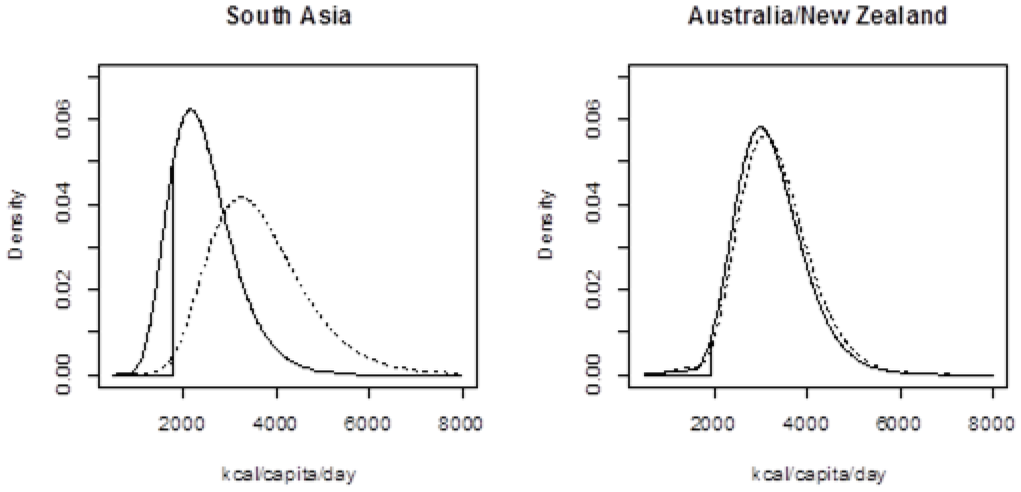

Figure 4.2: Probability Densities of Dietary Energy Consumption for South Asia and Australia/New Zealand Regions in 2006 (solid line) and in 2050 (dotted line)

becomes more inequitable (i.e. greater standard deviation), at a given average income level then the prevalence of malnutrition increases. Going forward in time, rising incomes lead to increased food consumption, and average dietary energy intake rises. This results in a thin tail to the left of the DEC distribution; hence, reduce the prevalence of caloric malnutrition.

The food security module is implemented using the food security data published by FAO (FAO, 2010, 2012) . Specifically, the data used include country-level figures on average per capita dietary energy intake, the share of food in total energy intake, and food quantities. These are then are used to compute the average dietary energy content of crops, livestock and processed foods consumed in each demand region. Since the FAO data on dietary energy and quantities do not account for wastage and/or losses at the household level, the estimates of final consumption are biased upwards.

To implement the growth elasticities, data on the MDER, average per capita DEC and standard deviation of the distribution of dietary energy are needed. The standard deviation is derived from published Gini indices of dietary energy intake from FAO (2010)[8]. These indices measure the equality of food distribution in a country. Larger values are associated with a more inequitable distribution of dietary energy and increased persistence of caloric malnutrition. Following Aitchison and Brown (1963), the formula below is used to calculate the standard deviation of the log-normal DEC distribution from the Gini indices:

$$\sigma = \sqrt{2}\left(\pi^{-1}\left[\frac{Gini+1}{2}\right]\right) \tag{3}$$

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[8] In this study, only Gini indices which are based on survey data starting from 1993 are used.

With the distributional parameters and consumption data in hand, the malnutrition index and gap index can now be derived for each demand region using the poverty-based formulas outlined by Lopez and Serven (2006). In calculating the food security metrics for the years 1991, 2001 and 2006, the parameter σ is adjusted for all regions using population-weighted malnutrition indices, MDERs and DECs from FAO (2012) as a guide.

Selected food security data for 2006 are summarized in the second column of Table 4.1. In reporting of nutritional outcomes, the discussions are aimed at key regions wherein chronic malnutrition is prevalent. These include: Sub-saharan Africa, Central Asia, China/Mongolia, Southeast Asia, South Asia, Central America and South America. Around 93% of the world's undernourished live in these regions with almost 60% residing in Sub-saharan Africa and South Asia. In Sub-saharan Africa, South Asia and Central Asia, roughly 1 out of 5 persons are malnourished as reflected in the malnutrition indices. High prevalence of caloric malnutrition in these regions is explained by the low levels of daily caloric consumption. Particularly in Sub-saharan Africa and South Asia, the average per capita caloric consumption is at least 15% less than the global average. Looking at the malnutrition gaps, it is obvious that the average depth of hunger in Central Asia, China/Mongolia, South Asia and Central America is greater than the world average. These regions are also characterized by the inequitable distribution of calories within its populace.

Table 4.1: Selected Food Security Statistics for Base Year 2006

Regions	Average Dietary Energy Consumption (kcal/capita/day)	Malnutrition Index (percent)	Malnutrition Gap (kcal/capita/day)	Malnutrition Count (million)	Standard deviation of caloric consumption
World	2761	12.0	235	764.2	-
Sub Saharan Africa	2110	23.5	207	157.7	0.23
Central Asia	2546	21.4	291	9.2	0.31
China/Mongolia	2989	9.6	250	127.6	0.31
Southeast Asia	2562	12.8	225	66.7	0.28
South Asia	2341	20.2	252	302	0.28
Central America	2909	10.1	252	19	0.33
South America	2903	8.2	221	30.8	0.29

4.3: Historical Validation

As mentioned in the preceding chapter, validating the model against the historical experience helps build confidence on the model's projections. Often studies which use economic models in order to project future outcomes do not validate their model against history, making it difficult to assess what the model does well and what it does poorly. Furthermore, this historical assessment also provides a useful context for examining changes in the future. The model is validated over the historical period 1991 to 2001 (10-years)[9]. Starting with a base data for year 2001 the model is 'back casted' from 2001 to 1991 given historical growth rates in population, per capita incomes and total factor productivity in the crops, processed foods and livestock sector. The corresponding food security statistics calculated for the year 1991 are then imposed. Going forward from 1991 to 2001, nutritional outcomes are simulated given shocks in population, per capita incomes and total factor productivity (TFP) growth in the crop, livestock and processed

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[9] The back casting experiment is limited by the availability of historical data on nutritional outcomes. The earliest period for which global nutritional data is available is for the period 1990-92.

food sectors. The simulated changes for the period 1991 to 2001 are then compared with the actual changes from published food security statistics. Table 4.2 lists the growth rates of the key drivers for this historical assessment. Growth rates for population and income are derived from the UN World Population Prospects (2013) and the World Bank's World Development Indicators (2011), respectively. TFP growth rates from the crop, livestock and processed food sectors are based on the historical estimates by Fuglie (2012), Ludena et al. (2007) and Griffith et al. (2004), respectively. Note that drastic changes in per capita incomes occurred during this short-run period, particularly for China and India which will likely exaggerate changes in food consumption. To control for this, it is important to impose the regional demand responses calculated for the year 2001. Finally, the simulated changes for the period 1991 to 2001 are compared with the actual changes from published food security statistics from FAO (2012).

Table 4.2: Per Annum Growth Rates of Key Variables for the Historical Period 1991-2001

Regions	Population	Per Capita Income	Total Factor Productivity		
			Crops	Livestock	Processed Food
Eastern Europe	-0.34	-2.37	0.83		
North Africa	1.60	1.57	1.94		
Sub Saharan Africa	2.77	-0.27	0.78		
South America	1.61	1.08	1.74		
Australia/New Zealand	1.20	2.32	1.44		
European Union+	0.26	2.02	2.10		
South Asia	1.90	3.60	1.16		
Central America	1.73	1.39	1.17		
Southern Africa	1.91	0.48	1.69		
Southeast Asia	1.64	2.60	1.62		
Canada/US	1.12	2.41	1.65		
China/Mongolia	0.85	9.38	2.01		
Middle East	2.01	1.18	1.42		
Japan/Korea	0.36	1.01	2.18		
Central Asia	1.67	-3.06	0.83		0.89
World				1.30	

The results of the historical validation are summarized in Figure 4.3. The figure illustrates that at both the global and regional level, SIMPLE broadly replicates the direction of the historical changes in average dietary intake, and malnutrition incidence and gap. However, it fails to capture the magnitude of these changes in food security metrics particularly at the regional level. Starting with the global outcomes, SIMPLE captures the direction but tends to overstate the rise in global average dietary energy intake (Figure 4.3, top panel). This in turn led to the overestimation of the observed reduction in the prevalence of malnutrition during this historical period (Figure 4.3, middle panel). Looking at the regional results, the most striking is the over-estimate of daily average DEC in South Asia (Figure 4.3, top panel) where, despite rising per capita income and falling prices, the reported DEC barely increases. As a consequence, the reduction in malnutrition incidence is overstated in this region (Figure 4.3, second panel). The model also overstates the increase in DEC, and the reduction in malnutrition incidence, in China. In contrast, in Central Asia, South East Asia, Central America and South America the changes in average dietary intake and malnutrition indices are underestimated. It is worth observing that SIMPLE picks up on the increase in malnutrition in Central Asia, although it greatly understates this increase. For Sub-Saharan Africa, the model predicts a negligible reduction in average DEC, yet FAO data shows an increase during the period, and therefore a reduction in malnutrition.

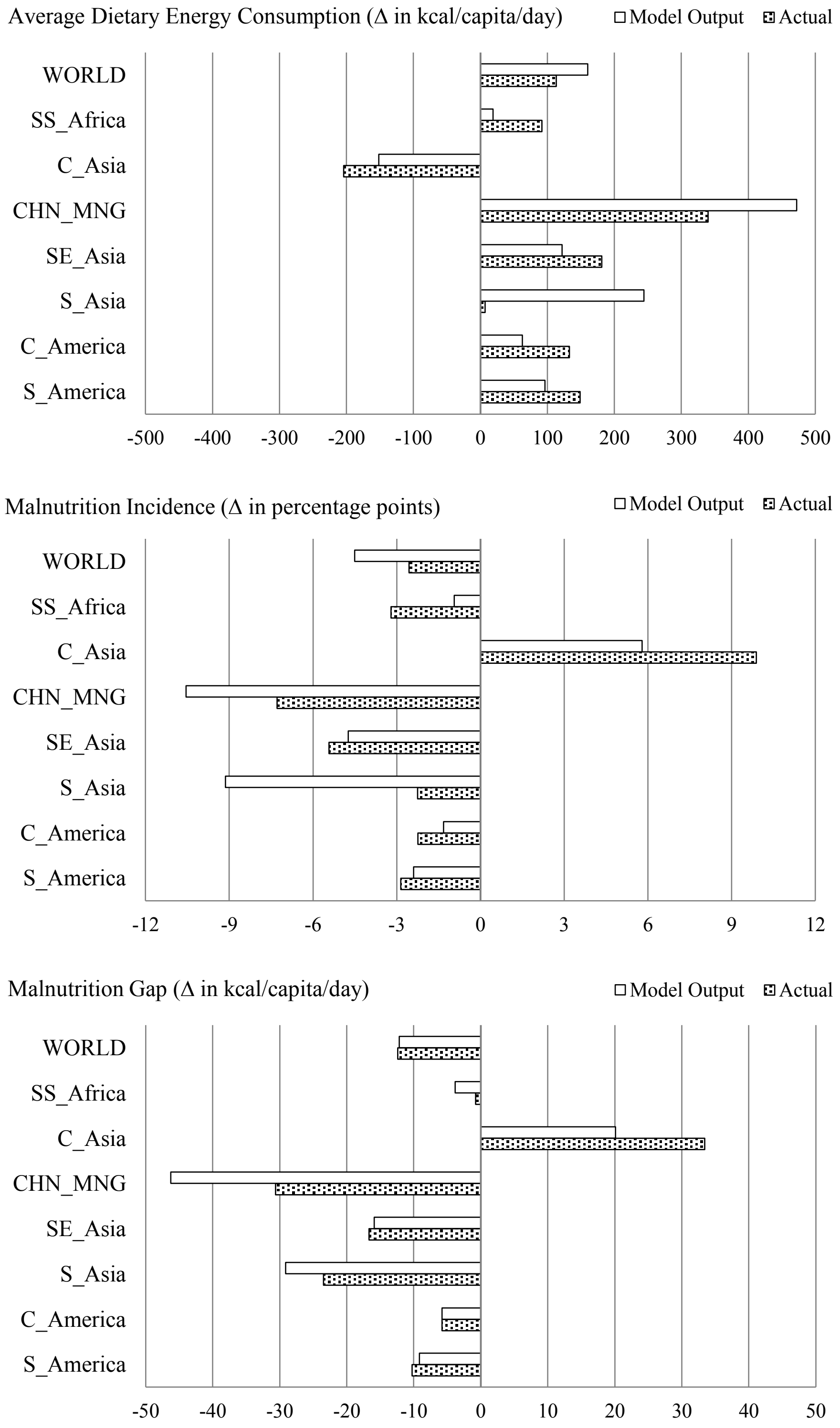

Figure 4.3: Selected Food Security Statistics from 1991 to 2001: Actual vs. Model Output

Despite the discrepancies in average DEC and malnutrition incidence, the simulated changes in the malnutrition gap closely follow actual changes in most regions (Figure 4.3, bottom panel). On average, the reduction in malnutrition gaps in South Asia and in China/Mongolia are overstated while the sharp rise in the depth of caloric malnutrition in Central Asia are understated during this period. Globally, these changes offset each other; hence the simulated reduction in the global malnutrition gap closely follows the actual decline.

The results of this validation exercise are instructive, suggesting that caution should be exercised when asserting precision in the regional projections. This is finding resonates with other studies seeking to validate global models. For example, in the comparison done by McCalla and Revoredo (2001), food balance projections from key international and national agencies were shown to become more prone to errors with greater levels of disaggregation. Even in developed countries wherein data are more reliable and available there are discrepancies between actual and simulated changes which the authors attribute to domestic policies. Baldos and Hertel (2013) validated the SIMPLE model over the period 1961 to 2006 (see Chapter 3) and found that, while it did a good job at predicting changes in global production, the model failed to accurately capture the distribution of crop production across regions. They noted that the inconsistencies may have been driven by domestic agricultural policies, foreign trade agreements and other barriers to international trade.

In the case of malnutrition, there are some good reasons to expect such deviations at the regional level. In Central Asia, the dramatic transition from centralized to market economies has affected food security in the region. After dissolution of the Soviet Union in the early 1990s, the lack of access to inputs and weakened institutions have led to the severe disruptions in domestic agricultural production and distribution (Babu & Tashmatov, 1999). Decreasing incomes coupled with higher food prices due to food shortages and rapid market liberalization have resulted in increased household expenditure on food, rising to levels observed in Sub-Saharan Africa and South Asia (Rokx, Galloway, & Brown, 2002). The persistence of malnutrition in India has continued to puzzle researchers. Deaton and Drèze (2009) report that caloric consumption in India has been declining despite improvements in rural and urban incomes, reductions in poverty rates and lower food prices. A closer look at the composition of food consumed shows that there seems to be a shift from cheaper to expensive sources of calories (e.g. grains to meats and dairy) which may explain the reduction in overall calories (Ray, 2007; Sen, 2005).

4.4: Experimental Design for Future Projections

Having tested the model against history, the next step is to implement a series of carefully designed scenarios to assess how global food security will be affected by population, per capita incomes, bioenergy policies, agricultural productivity and climate change. Starting with the baseline scenario for 2050, the impacts of population, per capita income growth, increased biofuel use and productivity improvements in the crop, livestock and processed food sectors are examined. In SIMPLE, productivity improvements are primarily captured through growth in total factor productivity (TFP). Going forward to 2050, it is assumed that TFP growth in the crops sector is input neutral while for the livestock and processed food sector, TFP growth is input-biased (i.e. biased towards non-crop inputs). With the baseline established, it is important to first explore the food security outcomes given stagnation in agricultural productivity (‘Demand only’ scenario). As mentioned in Chapter 3, TFP growth in agriculture was critical to the historic reduction of food prices since the 1960s. Going forward to 2050, this scenario only focuses on the demand shocks outlined in the preceding scenario to highlight the importance of productivity growth in driving future nutritional outcomes. In the next scenarios, the impacts of climate change on future global food security are assessed. Given the shocks in the baseline, crop yield effects from climate change if there is no CO_2 fertilization (‘No CO_2 fert.’ scenario) and if there is CO_2 fertilization (‘CO_2 fert.’ scenario) are both considered. These yield impacts are implemented as changes in TFP growth in the crops sector. Growth rates of each driver for the period 2006 to 2050 are listed Table 4.3. In the coming decades, population growth is expected to slow down relative to per capita income growth which highlights the importance of per capita income as a key driver of future food demand especially in developing regions. Additional demand for crops will also come from steady biofuel use worldwide. On the other hand, there is great uncertainty in the future of agricultural productivity particularly in the crop sector. While TFP growth in this sector is expected to slow down globally, regional yield shocks suggest that crop production in developing regions such as South and South East Asia as well as Sub Saharan Africa is quite vulnerable to climate change.

Table 4.3: Per Annum Growth Rates of Key Variables for the Future Period: 2006-2050

Regions	Population	Per Capita Income	Biofuels	Total Factor Productivity			Climate Change Yield Impacts	
				Crops	Livestock	Processed Food	CO_2 fert.	No CO_2 fert.
Eastern Europe	-0.36	4.75			1.04		0.39	0.02
North Africa	1.02	3.49			-0.30		-0.04	-0.32
Sub Saharan Africa	2.44	3.80			0.42		0.14	-0.16
South America	0.67	2.61			2.64		0.22	-0.17
Australia/New Zealand	1.04	1.62			0.42		0.07	-0.29
European Union+	0.11	1.34			0.50		0.31	0.02
South Asia	0.83	4.97			1.71		0.36	-0.36
Central America	0.84	2.40			2.64		0.22	-0.17
Southern Africa	0.64	2.62			0.42		0.14	-0.16
Southeast Asia	0.79	3.67			2.38		0.40	-0.35
Canada/US	0.66	1.01			0.42		0.23	-0.15
China/Mongolia	0.10	5.90			2.38		0.27	-0.07
Middle East	1.21	2.35			-0.25		-0.04	-0.32
Japan/Korea	-0.20	1.96			0.42		0.07	-0.29
Central Asia	0.96	4.90			1.04		0.39	0.02
World			5.80	0.94		0.89		

4.5: Results from Future Projections

All projections regarding selected food security outcomes for the year 2050 are summarized under the "Future Scenarios: 2050" column in Table 4.4. Starting with the baseline scenario for 2050, the table reports the future values of selected food security outcomes when both demand and supply drivers are implemented. In the future, the baseline suggests that population and agricultural productivity growth will be slower than in the 10-year historical period, whereas global biofuel use and per capita incomes continue their steady rise. The results show significant improvements in nutritional outcomes relative to 2006. Globally, average dietary energy intake increases by 24%

Table 4.4: Selected Food Security Statistics for Future Scenarios: 2006-2050

		Future Scenarios: 2050		
Regions	Baseline	Demand only	Climate Change:	
			No CO_2 fert.	CO_2 fert.
Average Dietary Energy Consumption (kcal/capita/day)		in Δ relative to Baseline		
World	3413	-587	-51	83
Sub Saharan Africa	2808	-478	-69	114
Central Asia	4095	-748	-75	123
China/Mongolia	4140	-907	-43	71
Southeast Asia	3187	-568	-47	77
South Asia	3513	-708	-74	120
Central America	3453	-625	-30	48
South America	3863	-824	-35	55
Malnutrition Index (percent)		in Δ relative to Baseline		
World	1.9	6.0	0.3	-0.4
Sub Saharan Africa	2.4	9.9	0.7	-0.8
Central Asia	1.0	3.7	0.2	-0.2
China/Mongolia	0.9	5.0	0.1	-0.1
Southeast Asia	2.8	8.4	0.4	-0.5
South Asia	1.2	5.9	0.3	-0.3
Central America	3.6	8.1	0.2	-0.3
South America	0.9	5.2	0.1	-0.1
Malnutrition Gap (kcal/capita/day)		in Δ relative to Baseline		
World	168	34	1	-2
Sub Saharan Africa	137	40	4	-7
Central Asia	183	36	3	-4
China/Mongolia	184	47	2	-3
Southeast Asia	177	42	3	-4
South Asia	162	42	3	-5
Central America	215	44	2	-3
South America	167	44	1	-2
Malnutrition Count (million)		in Δ relative to Baseline		
World	176.9	552.5	27.0	-35.1
Sub Saharan Africa	46.5	193.1	13.4	-16.1
Central Asia	0.7	2.4	0.1	-0.2
China/Mongolia	12.3	69.9	1.2	-1.7
Southeast Asia	20.9	62.0	2.7	-3.7
South Asia	25.6	126.9	5.4	-6.9
Central America	9.8	22.0	0.6	-0.9
South America	4.5	26.1	0.4	-0.6

while the prevalence and average depth of malnutrition further decrease by 84% and 29%, respectively. Sharp rises in average DEC are observed in South Asia, China/Mongolia and Central Asia – regions with modest per capita income growth rates – while notable reductions in the incidence of malnutrition in Sub Saharan Africa, Central Asia and South Asia are observed where malnutrition incidence falls sharply from around 20% in 2006 to less than 3% in 2050. Given these improvements, there is a significant reduction (around 77%) in the global malnutrition count which falls by 587 million between 2006 and 2050, despite increasing population. Most of these individuals who are lifted out of caloric malnutrition reside in South Asia, China/Mongolia and Sub-Saharan Africa. However, it is important to note that at both the global and regional level the percentage reductions in the prevalence of malnutrition are greater than in the malnutrition gap, highlighting the difficulty of reducing the average depth of malnutrition in the absence of improvements in the unequal distribution of DEC in these regions.

Figure 4.2 illustrates how the distribution of per capita dietary energy intake in a region shifts given the changes in average dietary energy consumption. Specifically, the probability densities of per capita DEC are compared for 2006 (solid line), obtained from published food security data (FAO, 2010, 2012), and for 2050 (dashed line), based on the baseline scenario, in both South Asia and Australia/New Zealand. The vertical solid line within each distribution represents the minimum dietary energy requirement. The area to the left of this line is the fraction of the population which is malnourished, having dietary energy intake below the MDER. Note that the DEC distribution is much more compact for Australia/New Zealand than for South Asia, suggesting a more equitable distribution of dietary energy. Under this framework, as the distribution of dietary energy intake becomes more inequitable (i.e. greater standard deviation), at a given average DEC, the prevalence of malnutrition increases. Going forward in time, rising incomes lead to increased food consumption, and average dietary energy intake rises. This results in a thin tail to the left of the DEC distribution. The reduction in malnutrition incidence is then determined by the difference between the areas bounded by the minimum dietary energy requirement and the caloric distribution curves in 2006 and in 2050.

The changes in the composition of food consumed between 2006 and 2050 under the baseline scenario are reported in Figure 4.4. Globally, the volume of food consumption increases by about 30%, most of which comes from increased consumption of livestock products and processed foods. Note that food prices in all regions are declining in 2050 under this scenario which suggest that agricultural productivity growth in the coming decades may exceed the growth in future food demand due to rising population and incomes (Column A, Appendix F). In regions with relatively low per capita incomes at present but face modest income growth in the future, there are larger increases in food consumption. These consist of Central Asia, Sub-Saharan Africa and South Asia wherein food consumption increases by around 52% to 73%, nearly all of which comes from increased consumption of livestock commodities. Note that in SIMPLE, consumer responses to income and prices decline as per capita income rises and it declines faster for crops relative to livestock and processed foods. Given this, additional income will be spent disproportionately on livestock and processed foods.

Note that the increase in food consumption is greater than the increase in average DEC. This is due to the changes in caloric content of food (Figure 4.1). Higher incomes facilitate quality upgrading which may result in fewer calories per dollar spent on a given food type – as observed in crops and processed foods – as well as consumers' shift to a leaner and higher quality diet.

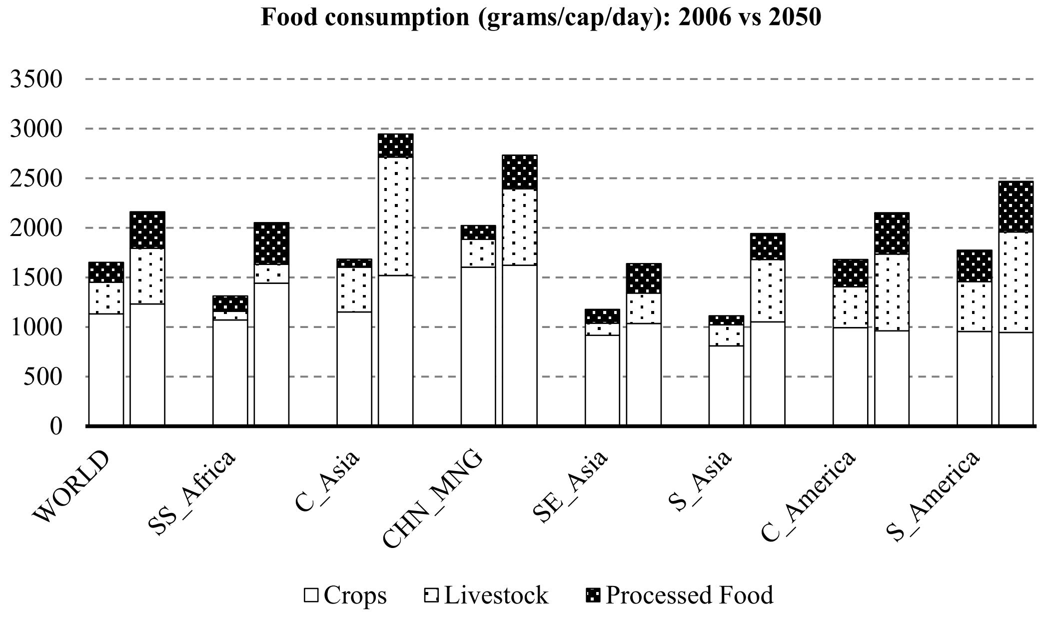

Figure 4.4: Composition of Food Consumption in 2006 and 2050

Returning to the scenarios reported in Table 4.4, the 'Demand only' scenario shows the nutritional attainment when the supply-side drivers are ignored. This scenario isolates the impact of agricultural productivity growth on nutritional attainment. Note that the columns of Table 4.4 report the *differences* in food security outcomes relative to the baseline scenario in 2050. The results show that the improvements in nutritional outcomes are severely dampened if agricultural productivity stagnates. Note that without TFP growth, prices of all food aggregates will rise and even exceed price levels in 2006 (Column A, Appendix F). Rising food prices is detrimental to food consumption in developing regions since lower income consumers are relatively more responsiveness to price changes (Column D, Appendix F) since a significant portion of their income is spent on food. With higher prices, the increase in commodity consumption due to higher income growth will be dampened.

With only the demand drivers in place, the prevalence of malnutrition exceeds that in the baseline by more than four times (7.9% vs. 1.9%). Regions wherein the malnutrition incidence falls more slowly relative to the baseline include: Sub-Saharan Africa, South Asia and South East Asia. With rising incidence, the average depth of malnutrition in these regions also falls at a slower pace relative to the baseline. Under this scenario, the global malnutrition count between 2050 and 2006 declines slightly to 729 million people. However, across regions the increase in malnutrition count will be higher in the poorest countries, where the response to higher prices is most accentuated. Thus the malnutrition headcount in Sub-Saharan Africa rises by 193 million, relative to the baseline. Under this (no productivity growth) scenario, more than one-third of the world's malnourished may reside in this region by 2050. In sum, because of the high population growth in the coming decades, food security in this region is quite vulnerable to any setbacks in agricultural productivity growth. The results from the 'Demand only' scenario reaffirm the findings in the literature regarding the importance of productivity growth in agriculture and how these improvements strengthen food security, particularly in regions of the world wherein chronic malnutrition is prevalent (G. Nelson et al., 2010; Schneider et al., 2011).

In the following scenarios, changes in nutritional outcomes in light of potential crop yield impacts of climate change are explored in the presence or absence of CO_2 fertilization using the yield estimates from Müller *et al* (2010). Rising CO_2 levels can directly benefit crop yields by stimulating photosynthesis and promoting water use efficiency for C3 crops such as wheat and rice (Long *et al*. 2004). Early estimates suggest that by mid-century the fertilization effect from boosted CO_2 levels in the atmosphere could increase average yields of C3 crops by around 13% (Long *et al*. 2006). However, recent analysis at the grid-cell level shows that CO_2 impacts differ widely across crop types as well as agro-climatic conditions (McGrath & Lobell, 2013). Moreover, 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 (David B. Lobell & Gourdji, 2012). These findings suggest that there is great uncertainty on how CO_2 fertilization will affect crop yields in the future and such uncertainty will certainly be reflected in the projections of nutritional outcomes in 2050.

Without CO_2 fertilization ('No CO_2 fert.'), crop yields in most regions will be adversely affected by the temperature and precipitation impacts from climate change. Globally, yields will decline by around 1.3% per decade under this scenario, which is close to the expected reduction (1.5% per decade) in the literature (David B. Lobell & Gourdji, 2012). With relatively lower crop yields under this scenario, the reduction in crop prices from projected crop TFP growth will be slightly dampened. At a glance, the gains in food security from 2006 to 2050 are reduced relative to the baseline scenario. At both global and regional levels, the change in average DEC increases and average depth of malnutrition are negligible. However, the *relative* reduction in average DEC is greater (around 35% more than the global reduction) in Sub-Saharan Africa and South Asia wherein consumers are more responsive to food prices. The gravity of climate change impacts on food security is quite evident on the prevalence of malnutrition. At the global level, malnutrition incidence increases by about 16% relative to the baseline scenario. Across regions, the increase in the prevalence of malnutrition is more than 20% in Sub-Saharan Africa and South Asia. Coupled with the steady growth in population, global malnutrition count actually increases under this scenario (by about 27 million, relative to the baseline) most reside in Sub-Saharan Africa and South Asia.

When the effects of CO_2 fertilization are added in ('CO_2 fert.'), crop yields are higher in most regions of the world (by 2.2% per decade globally), resulting in slightly lower crop prices and further improvements in food security outcomes particularly for the poorest regions of the world. However, similar to the previous case, it is difficult to see these gains explicitly just by looking at the average DECs but relative to the increase in the global average, there is evidence of strong gains (by more than 37 percent) in average dietary energy intake in Sub Saharan Africa, Central Asia and South Asia. With CO_2 fertilization in place, the global malnutrition incidence further declines by 20 percent relative to the baseline. Regions which benefit most from reduced malnutrition headcount under this scenario are Sub-Saharan Africa, South East Asia and South Asia. With CO_2 fertilization effects, the number of malnourished persons globally further declines by around 35 million relative to the baseline. The results from the previous scenarios illustrate the uncertainty posed by climate change on global food security as it may enhance or dampen improvements in nutritional outcomes in the future depending on the strength of the yield impacts of CO_2 fertilization. More importantly, these impacts are further magnified in lower income regions wherein consumers are more responsive to changes in food prices. Furthermore, these results highlight the importance of looking at nutritional outcomes that incorporate the distribution of caloric energy across world region. These differences are barely observed in the average dietary energy intake in the baseline and the scenarios with climate change yield impacts. However, as evidenced by the changes in the prevalence and headcount of malnutrition, climate change could have significant implications on the nutritional outcomes of millions of people particularly for those living in hunger-stricken regions of the world.

To better understand how each driver affects past and future food security outcomes, it is critical to evaluate the contribution of each of the exogenous drivers to the simulated changes in the malnutrition count for the historical period 1991 to 2001 (top panel) and for the 'Climate Change no CO_2 fert.' Scenario (bottom panel) (Table 4.5). The subtotals feature in GEMPACK which was developed by Harrison, Horridge and Pearson (2000) is used for this analysis (see Chapter 3). The authors note that estimating the contribution of exogenous shocks in general equilibrium models will depend on the assumed path from one equilibrium point to another. They propose a numerical integration technique that exactly partitions the impacts of different exogenous shocks on endogenous variables of interest under the assumption that the assumed path is a straight line. This tool is critical in the analysis of the relative contribution of each key driver of global food security.

The second column of Table 4.5 shows the total change in the malnutrition count while the rest of the columns summarize the contribution of each driver to the total change. Rather than reporting the resultant changes in malnutrition count directly, the individual impacts of per capita incomes, biofuel use, TFP and climate change are reported relative to the impact of population to facilitate comparison of their relative importance.

Table 4.5: Contribution of Selected Drivers on Malnutrition Count

Regions	Total Change	Contribution of Population	Contribution relative to Population (Index=100)			
			Per Capita Income	Biofuels	TFP	Climate Change: No CO_2 fert.
Malnutrition Count (millions)						
Historical Experiment: 1991 to 2001						
World	-150.7	266.5	-47	-	-109	-
Sub Saharan Africa	44.6	73.7	25	-	-64	-
Central Asia	3.6	2.9	135	-	-112	-
China/Mongolia	-117.7	40.8	<-200	-	-149	-
Southeast Asia	-7.8	28.5	-18	-	-110	-
South Asia	-74.0	93.9	-63	-	-116	-
Central America	1.2	5.2	16	-	-94	-
South America	-1.7	10.6	5	-	-121	-
Climate Change no CO_2 fert.: 2006 to 2050						
World	-560.0	276.6	-159	6	-166	16
Sub Saharan Africa	-97.8	145.0	-91	5	-94	13
Central Asia	-8.4	1.9	<-200	7	-171	17
China/Mongolia	-114.0	10.0	<-200	15	<-200	35
Southeast Asia	-43.2	22.9	-104	7	<-200	18
South Asia	-271.0	64.2	<-200	9	<-200	21
Central America	-8.6	7.0	-14	4	<-200	11
South America	-25.8	6.3	-156	6	<-200	16

Starting with the historical period, population growth alone contributed to an increase in the global malnutrition count by 266 million persons. Note that this contribution is large since there is a larger base of malnutrition headcount in 1991 (around 833 million). The impacts of income and TFP growth on the world malnutrition headcount over this historical period are around 47% and 109% as large as the population impact, and opposite in sign, respectively. As a consequence of income and TFP growth, malnutrition count fell over this period. In most regions, the primary force in reducing malnutrition headcount is TFP. For China/Mongolia, per capita income is the main driver of lower malnutrition count. Next, the results of the forward-looking, ‘No CO_2 fert.’ scenario are decomposed (bottom panel of Table 4.5).The decomposition shows that population growth, increased biofuel use and climate change all contribute to greater food insecurity at the global level while growth in per capita incomes and TFP improve nutritional outcomes. The individual impact of population on the global malnutrition count is 277 million which is smaller than the historical impact – although the future period is more than four times as long. This is mainly due to a smaller base of malnutrition headcount in 2006 (around 764 million) and the sharp slowdown in population growth over this future period. At the regional level, population becomes an important driver of malnutrition count in Sub-Saharan Africa, South Asia and South East Asia – regions with steady population growth rates in the coming decades. The individual impacts of rising per capita incomes, increased biofuel use, TFP growth and climate change yield effects are also reported in Table 4.5. As with the historical analysis, these are expressed relative to the contribution of population growth. At the global level, the reduction in malnutrition headcount will be mainly driven by TFP growth followed by per capita income growth. Projections for South Asia and China/Mongolia suggest that per capita income will be the key driver. However, in light of the historical puzzle of reduced caloric consumption, despite rising incomes in South Asia, some caution should be attached to this finding.

Examining the relative impacts of increased biofuel use and climate change yield effects, estimates suggest that their contribution is far significant than that of population, income or TFP. Given the assumed growth rates in the future experiments, increased biofuel use is the least important driver of food security in the coming decades. It has roughly 6% of the contribution of population growth on global malnutrition count. Climate change in the case of no CO_2 fertilization has a greater impact than increased biofuel use. Globally, the contribution of this characterization of climate change is around 16% of the contribution of population on the changes in the malnutrition count, respectively. This is consistent with the assessment of Schmidhuber and Tubiello (2007) regarding the food security impacts of climate change. The authors reviewed the literature and noted that the potential impact of climate change on the headcount of people at risk of hunger is relatively smaller than the impact of socio-economic drivers such as population and per capita incomes. However, as revealed in the analysis, climate change could still pose significant risk on the food security of people residing in regions wherein chronic malnutrition in persistent.

4.6: Summary and Conclusions

This chapter examines how global food security will be affected in 2050 given the projected trends in the underlying drivers of the world farm and food system using the SIMPLE model and the food security module. This module calculates the headcount, prevalence and average depth of malnutrition and allows the assessment of the contribution of these drivers on nutritional outcomes. To build confidence in the projections, the model is evaluated against an historical experiment from 1991 to 2001, based on historical growth rates in population, per capita incomes and TFP. The results indicate that at the global level SIMPLE can closely replicate the observed increase in the average dietary energy intake while also doing a reasonable job capturing reductions in the malnutrition incidence and gap, respectively. Turning to the regional level, model performance is less satisfactory. Accurately predicting the changes in regional malnutrition – particularly in South Asia – has posed a major challenge in the literature and the SIMPLE model is not immune to this problem.

Looking ahead from 2006 to 2050, nutritional outcomes are projected given future growths in population, per capita incomes, biofuel use and TFP. A separate assessment of the impacts of climate change in agricultural productivity is also considered. In the future, population growth is projected to slow down while biofuel use, per capita incomes and agricultural productivity are expected rise steadily. The net effect of these diverse drivers is to reduce in the global malnutrition incidence, count and gap particularly in the poorest regions of the world. When TFP growth is removed from the picture, nutritional outcomes worsen, with virtually no reduction in the global headcount over the 2006-2050 period. This highlights the importance of increasing productivity growth in agriculture in order to improve food security outcomes in the coming decades. The impact of climate change on future nutritional outcomes is uncertain. Depending on the strength of the yield impacts of CO_2 fertilization, climate change may strengthen or weaken the future gains in global food security. Overall, the results from these scenarios illustrate the importance of looking at nutritional outcomes based on distribution of caloric consumption since changes in the average dietary energy consumption under climate change are negligible, while changes in malnutrition prevalence and headcount are substantially greater.

The analysis of the individual drivers of global food security shows that, over the historical period from 1991 to 2001, population and TFP were the dominant drivers of malnutrition. At the global level, the impact of population on malnutrition headcount exceeded that of per capita income during this historical period. Going forward to 2050, the relative impact of population on global malnutrition count will be offset by the relative contribution of per capita income and TFP growth. On average, the contribution of biofuels and climate change are far lower than that of the other drivers. These results suggest that future nutritional outcomes will be mainly affected by socio-economic conditions as well as productivity trends in the agricultural sector. However, climate change will still be a relevant driver of nutritional outcomes especially for those residing in regions of the world where chronic malnutrition is prevalent.

Note that food security is quite dependent on the assumed growth of TFP in the coming decades; hence, future work regarding this study should devote greater attention to the sources of future productivity growth. Furthermore, the implications of TFP and climate change will be magnified for some regions if they are not fully integrated in the world food markets. These areas for future work along with those mentioned in the previous chapters are further discussed Chapter 5.

CHAPTER 5. DIRECTIONS FOR FUTURE RESEARCH

This dissertation examined the importance of productivity growth in shaping the historical changes in production, land use and prices and its impact on future nutritional outcomes. In Chapter 2, trends in Total Factor Productivity growth – a measure which accounts for all farm outputs and inputs – is computed in the context of the Indian crops sector. Despite the lethargic TFP growth in the northern region, productivity grew strongly in the rest of India; thus, TFP rose by 1.42% per annum at the national level from 1999-2000 to 2009-2010. This suggests that the stagnation in Indian agriculture documented during the 1980s to 1990s may have been reversed in the 2000s. In particular, sharp TFP growth is observed in the late 2000s both at national and regional level. Experts attribute exceptional performance during this period to crop diversification, high global food prices, and investments in agricultural research and development. In addition, the decomposition of the sources of output growth shows that TFP growth – rather than increased input use – is the main driver of output trends during this period. Going forward, it is important to improve the estimates of TFP growth by calculating these rates for each year. The current study only looks at 3 points in a decade (i.e. 1999-2000, 2004-2005, 2009-2010); thus, the estimated TFP growth rates might not fully characterize crop productivity trends during the 2000s. More importantly, it is critical to identify the drivers of crop TFP growth in India. In the literature, TFP growth is linked to public investments in agriculture, agricultural research and development, roads and infrastructure as well as irrigation. Furthermore, rather than just looking at its contribution to over-all output growth, the implications of TFP growth for poverty incidence and nutritional outcomes warrant further exploration. An explicit assessment of the sources and welfare impacts of TFP growth is particularly useful for policy makers who are interested in identifying options for sustained productivity growth and its potential gains.

A more thorough discussion of the implications of productivity growth requires a formal economic model of agriculture. And this dissertation develops such a framework for use at global scale: the SIMPLE model. In Chapter 3, the SIMPLE model is used to demonstrate the challenges encountered when validating global models of agriculture against history. Given the long-run historical period 1961 to 2006, the results from the "back-casting" experiment suggest that SIMPLE can replicate the historical changes in global crop production, average yields, cropland use and prices. However, the performance at the regional level is less satisfactory since it ignores other drivers of agriculture – such as international trade – which influence the distribution of crop production across the world.

The current version of SIMPLE is calibrated such that there is an integrated world market for crop (i.e. a global crop price). Of course, this is far from reality since some regions are not fully integrated in the world market during this historical period. Future work should focus on segmenting the crop markets into domestic and international sources by building in an Armington trade framework in SIMPLE. The Armington trade structure has been traditionally used in computational economic models of international trade and preliminary results from a modified version of SIMPLE shows that, by segmenting domestic from international commodity markets, it can help reconcile much of the discrepancy between actual and simulated changes at the regional level. This modification will also help enrich future projections from the model by tracking of trade flows in crop markets and allowing the assessment of increased market integration on both global and regional changes in crop production, land use and prices.

Going forward to 2050, Chapter 4 highlights the implications of productivity growth and climate change impacts on food security. The results show the importance of sustained agricultural productivity growth in order to improve food security outcomes in the coming decades. Given this, it is important to adopt credible TFP growth projections for 2050. This can be pursued by directly linking productivity growth to changes in private and public spending in agricultural research. With this framework, it is possible to directly measure the improvements in nutritional outcomes given a specified increase in spending on both public and private agricultural research. Climate change introduces uncertainty in future agricultural productivity growth and nutritional outcomes especially when CO_2 fertilization is considered. Of course, it is important to recognize that there is also uncertainty in the projected growth rates of exogenous drivers and model parameters. To better incorporate uncertainty in future projections, Monte Carlo analysis can be used. By introducing distributions of model parameters and shocks, it is possible to create confidence intervals which will help identify the likely values of food security outcomes as well as crop production, price and land use by mid-century.

The SIMPLE model can be easily extended and applied to examine broader issues related to global agriculture. In this dissertation, the environmental implications of increased crop production have not been fully examined. However, it is well documented that the excessive use of modern farm inputs such as fertilizers and pesticides can have adverse impacts on the environment through leaching and runoff. Furthermore, the expansion of crop land in carbon-rich forest areas releases additional GHGs into the atmosphere which further contributes to climate change. A first cut approach to incorporating the environmental impacts from increased crop production is to attach emission factors which convert the use of land and non-land inputs into environmental measures such as GHGs. This modification allows us to examine GHG emissions stemming from cropland expansion and intensification of production. More importantly, this improvement can help quantify the potential gains from avoided environmental emissions due to increased productivity growth. Currently, GHG emissions factors from land use change have been implemented in SIMPLE (D. B Lobell et al., 2013) and this can be extended to reflect non-land inputs such as fertilizer use.

Irrigated water use in agriculture can also be incorporated into SIMPLE. Data on water usage during crop production can be combined with the Armington trade framework in order to track the flows of irrigated water resources embodied in crop commodities across world regions (i.e. virtual water trade). These improvements will can also make it is possible to introduce further details on the effects of climate change since crop yield impacts are dampened in affected areas equipped with irrigation. Dwindling water resources in key regions of the world will also likely limit the prospects for future expansion of irrigated lands. Thus, including irrigated cropland in SIMPLE can help enrich the analysis of future forecasts on food prices, production and nutritional outcomes.

In summary, the SIMPLE framework developed in this dissertation offers a useful lens through which to look at a variety of factors bearing on the long run sustainability of the global food system. It has also been used in the context of an inter-disciplinary graduate course on this topic wherein students execute lab assignments with SIMPLE and then undertake projects using this framework. In this context, it has proven itself to be a robust and flexible vehicle for examining the interplay between agricultural production, land use, food security and the environment.

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APPENDICES

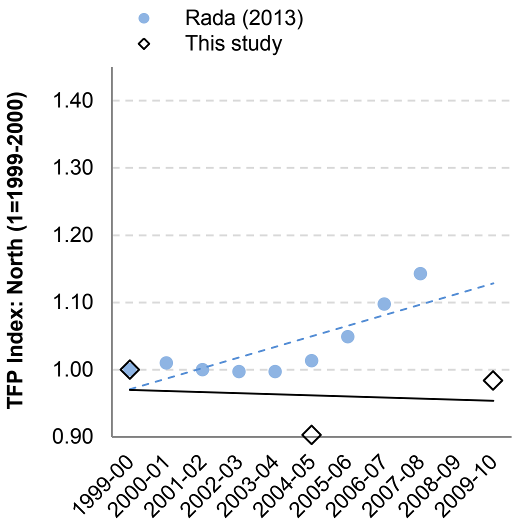
Appendix A: Coverage of states, crops and inputs

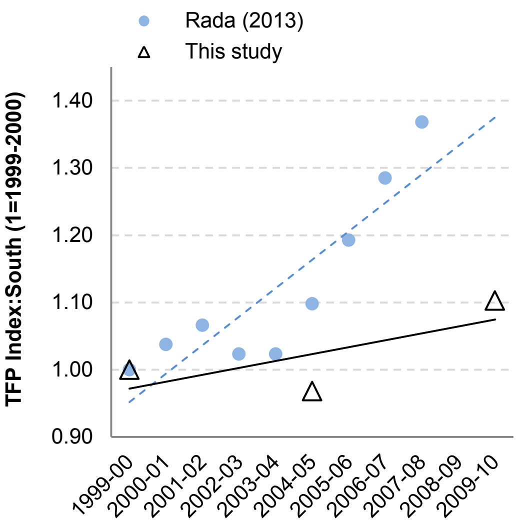
State		Crop		Input	
Haryana	North	Bajra	Cereals	Seed	Seed
Himachal Pradesh		Barley		Fertilizer	Fertilizer + Manure
Punjab		Jowar		Manure	
Uttar Pradesh		Maize		Land	Land
Andhra Pradesh	South	Paddy		Human Labor: Family	Human Labor
Karnataka		Ragi		Human Labor: Attached	
Kerala		Wheat		Human Labor: Casual	
Tamil Nadu		Cotton	Fibre crops	Animal Labor: Hired	Animal Labor
Assam	East	Jute		Animal Labor: Owned	
Bihar		Nigerseed	Oilseed	Machine Labor: Hired	Machine Labor
Orissa		Rapeseed & Mustard		Machine Labor: Owned	
West Bengal		Safflower			
Gujarat	West	Sesamum			
Madhya Pradesh		Soybean			
Maharashtra		Sunflower			
Rajasthan		Arhar	Pulses		
		Gram			
		Sugarcane	Sugarcane		

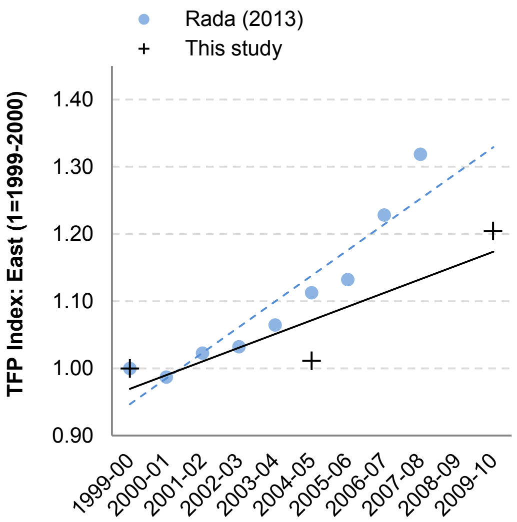
Appendix B. State-level Growth Rates of Output, Input and TFP: 1999-2000, 2004-2005 and 2009-2010

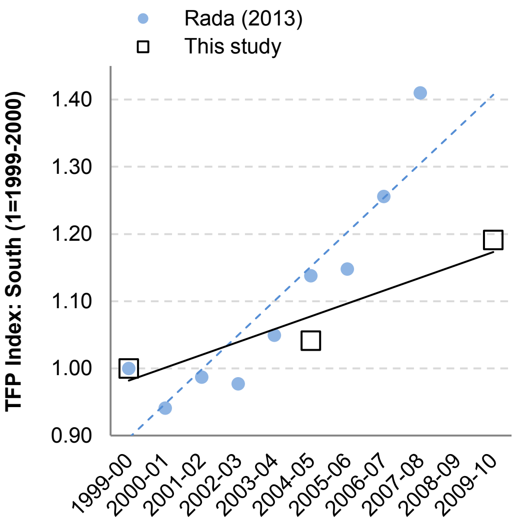
States	Average Annual Growth Rate: 1999-2000 to 2004-2005			Average Annual Growth Rate: 2004-2005 to 2009-2010			Average Annual Growth Rate: 1999-2000 to 2009-2010		
	Output index	Input index	TFP index	Output index	Input index	TFP index	Output index	Input index	TFP index
Andhra Pradesh	0.36%	-1.38%	1.73%	2.48%	0.05%	2.44%	1.44%	-0.63%	2.07%
Assam	-2.22%	-2.66%	0.43%	4.41%	0.63%	3.78%	1.09%	-0.95%	2.04%
Bihar	-14.34%	-7.18%	-7.16%	5.98%	-0.52%	6.50%	-3.63%	-3.83%	0.20%
Gujarat	11.23%	9.75%	1.47%	6.84%	2.11%	4.73%	9.91%	5.88%	4.03%
Haryana	1.89%	1.44%	0.45%	1.94%	-0.16%	2.10%	1.92%	0.60%	1.32%
Himachal Pradesh	2.46%	0.99%	1.47%	-11.02%	-3.32%	-7.70%	-4.22%	-1.09%	-3.13%
Karnataka	-2.11%	-1.28%	-0.84%	3.57%	-0.51%	4.08%	0.11%	-0.64%	0.74%
Kerala	-2.89%	-4.60%	1.71%	-2.18%	-6.40%	4.22%	-2.53%	-5.56%	3.03%
Madhya Pradesh	-8.55%	-5.73%	-2.81%	5.74%	0.65%	5.10%	-1.05%	-2.43%	1.37%
Maharashtra	-4.98%	-1.87%	-3.11%	9.90%	3.86%	6.04%	1.67%	1.06%	0.61%
Orissa	4.24%	-2.77%	7.02%	1.36%	-0.54%	1.90%	2.79%	-0.60%	3.39%
Punjab	1.83%	0.78%	1.05%	0.91%	-0.47%	1.38%	1.45%	0.10%	1.35%
Rajasthan	5.44%	1.34%	4.10%	-2.05%	-0.20%	-1.85%	1.89%	0.56%	1.32%
Tamil Nadu	-7.99%	-5.05%	-2.95%	2.78%	-1.21%	4.00%	-2.60%	-3.13%	0.54%
Uttar Pradesh	-2.29%	11.78%	-14.07%	1.85%	0.22%	1.63%	-0.86%	6.12%	-6.98%
West Bengal	3.34%	2.93%	0.42%	2.59%	-0.04%	2.63%	2.69%	1.34%	1.35%

Appendix C. Comparison of TFP Estimates: Regional-level









Appendix D. Mathematical Description of SIMPLE

SETS/INDICES

Commodities

$i = (Crops, Livestock, Proc\_Food, Non\_Food)$

Income Regions[10]

$y = (Up\_Higher, Low\_Higher, Up\_middle, Low\_middle, Low)$

Geographic Regions[1]

$g =$
$(E\_Asia\_Pac, Eur\_C\_Asia, L\_Amer\_Carr, M\_East\_N\_Afr, N\_America, S\_Asia, S\_S\_Africa)$

PARAMETERS

$\varepsilon_{P(i,y)}$	price elasticity of commodity demand
$\varepsilon_{Y(i,y)}$	income elasticity of commodity demand
$\alpha_{P(i)}$	intercept of price elasticity regression with log of per capita income
$\alpha_{Y(i)}$	intercept of income elasticity regression with log of per capita income
$\beta_{P(i)}$	slope of price elasticity regression with log of per capita income
$\beta_{Y(i)}$	slope of income elasticity regression with log of per capita income
$\sigma_{CROP(g)}$	substitution elasticity between cropland and non-land inputs
σ_{PRFD}	substitution elasticity between crops and non-crop inputs in the processed food sectors
σ_{LSTK}	substitution elasticity between feed and non-crop inputs in the livestock sectors
$\varepsilon_{LAND(g)}$	cropland supply response to cropland rents
$\varepsilon_{NLAND(g)}$	non-land supply response to non-land prices
$\theta_{LAND(g)}$	cost share of croplands
$\theta_{NLAND(g)}$	cost share of non-land inputs
$\theta_{CRPFOOD(y)}$	cost share of crop inputs in the processed food sectors
$\theta_{NCRPFOOD(y)}$	cost share of non-crop inputs in the processed food sectors
$\theta_{CRPFEED(y)}$	cost share of feeds in the livestock sectors
$\theta_{NCRPFEED(y)}$	cost share of non-crop inputs in the livestock sectors

VARIABLES

Note: Lower case letters refer to the percentage change in the LEVELS variables (i.e. UPPER CASE letters). They are linked in the model code through update equations and the non-linear model is solved as an initial value problem using the GEMPACK program[11].

Quantities

$q_{PC(i,y)}$	per capita commodity demand
$q_{(i,y)}$	regional commodity demand
$x_{LAND(g)}$	cropland area
$x_{NLAND(g)}$	non-land input quantity
$x_{CRPFEED(y)}$	feeds used in the livestock sectors
$x_{NCRPFEED(y)}$	non-crop inputs used in the livestock sectors
$x_{CRPFOOD(y)}$	crop inputs used in the processed food sectors
$x_{NCRPFOOD(y)}$	non-crop inputs used in the processed food sectors
$x_{CRPBIOF}$	crop feedstock used in the global biofuel sector

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[10] In the 15-region version of SIMPLE is based on the geographic regions only

[11] Harrison, W. J., & Pearson, K. R. (1994). Computing Solutions for Large General Equilibrium Models Using GEMPACK. Monash University, Centre of Policy Studies/IMPACT Centre.

Prices

p_{CROP}	global crop price
$p_{(i,y)}$	price of commodity
$p_{LAND(g)}$	cropland rent
$p_{NLAND(g)}$	non-land prices
$p_{NCRPFOOD(y)}$	price of non-crop inputs in the processed food sectors
$p_{NCRPFEED(y)}$	price of non-crop inputs in the livestock sectors

Other variables

$y_{PC(y)}$	per capita income
$pop_{(y)}$	population
$TFP_{CROP(g)}$	total factor productivity in the crop sector
$TFP_{LIVESTOCK(y)}$	total factor productivity in the livestock sector
$TFP_{PROC\_FOOD(y)}$	total factor productivity in the processed food sector
$AO_{(g)}$	input neutral productivity change in the crop sector
$AF_{(i,y)}$	input-biased productivity change (livestock and processed food sectors only, non-crop input-augmenting technical change)

EQUATIONS

There are three broad types of equations in the model: consumer demands, food and agricultural supplies, and commodity market clearing. Consumer demands are simple log-linear relationships in which the own-price and income elasticities vary as a function of per capita income level. The supply equations for crops, livestock and processed foods are based on non-linear Constant Elasticity of Substitution (CES) production functions. These are readily expressed in linearized form (i.e. percentage change) at shown below. Note that when this model is solved with the linearized-levels variable linkages, we obtain the same solution as would be obtained by implementing the model in levels form. There is only one commodity market clearing condition in this model, and that is for crops at global scale. For more details on this mixed, linearized-levels representation of an economic model, see Hertel, Horridge and Pearson (1992)[12].

Consumer demand equations

$\varepsilon_{P(i,y)} = \alpha_{P(i)} + \beta_{P(i)} \ln[Y_{PC(y)}]$	predicted price elasticities wrt. per capita income
$\varepsilon_{Y(i,y)} = \alpha_{Y(i)} + \beta_{Y(i)} \ln[Y_{PC(y)}]$	predicted income elasticities wrt. per capita income
$q_{PC(i,y)} = \varepsilon_{P(i,y)} p_{(i,y)} + \varepsilon_{Y(i,y)} y_{PC(y)}$	per capita commodity demand
$q_{(i,y)} = q_{PC(i,y)} + pop_{(y)}$	regional commodity demand

Crop supply/production equations

$x_{LAND(g)} = x_{CROP(g)} - ao_{(g)} - \sigma_{CROP(g)}[p_{LAND(g)} - p_{CROP} - ao_{(g)}]$	derived demand for cropland
$x_{NLAND(g)} = x_{CROP(g)} - ao_{(g)} - \sigma_{CROP(g)}[p_{NLAND(g)} - p_{CROP} - ao_{(g)}]$	derived demand for non-land
$p_{CROP} = ao_{(g)} + \theta_{LAND(g)} p_{LAND(g)} + \theta_{NLAND(g)} p_{NLAND(g)}$	zero profit condition
$x_{LAND(g)} = \varepsilon_{LAND(g)} p_{LAND(g)}$	cropland supply
$x_{NLAND(g)} = \varepsilon_{NLAND(g)} p_{NLAND(g)}$	non-land supply

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[12] Hertel, Thomas W., J. Mark Horridge, and Kenneth R. Pearson, 1992. "Mending the Family Tree: A Reconciliation of the Linearization of Levels Schools of Applied General Equilibrium Modeling," Economic Modeling, 9:385-407.

Livestock supply/production equations

derived demand for feeds

$$x_{CRPFEED(y)} = q_{("Livestock",y)} - \sigma_{CRPFEED}\left[p_{CROP} - p_{("Livestock",y)}\right]$$

derived demand for non-crop inputs

$$x_{NCRPFEED(y)} = q_{("Livestock",y)} - af_{("Livestock",y)} - \sigma_{CRPFEED}\left[p_{NCRPFEED(y)} - p_{("Livestock",y)} - af_{("Livestock",y)}\right]$$

zero profit condition

$$p_{("Livestock",y)} = \theta_{CRPFEED(y)}p_{CROP} + \theta_{NCRPFEED(y)}\left[p_{NCRPFEED(y)} - af_{("Livestock",y)}\right]$$

Processed food supply/production equations

derived demand for crop inputs

$$x_{CRPFOOD(y)} = q_{("Proc\_Food",y)} - \sigma_{CRPFOOD}\left[p_{CROP} - p_{("Proc\_Food",y)}\right]$$

derived demand for non-crop inputs

$$x_{NCRPFOOD(y)} = q_{("Proc\_Food",y)} - af_{("Proc\_Food",y)} - \sigma_{CRPFOOD}\left[p_{NCRPFOOD(y)} - p_{("Proc\_Food",y)} - af_{("Proc\_Food",y)}\right]$$

zero profit condition

$$p_{("Proc\_Food",y)} = \theta_{CRPFOOD(y)}p_{CROP} + \theta_{NCRPFOOD(y)}\left[p_{NCRPFOOD(y)} - af_{("Proc\_Food",y)}\right]$$

Market clearing equations

$$p_{CROP} = p_{("Crops",y)}$$

integrated world price for crops

$$\sum_{g=1}^{7} X_{CROP(g)} = \sum_{i=1}^{5}\left[Q_{("Crops",y)} + X_{CRPFEED(y)} + X_{CRPFOOD(y)}\right] + X_{CRPBIOF}$$

market clearing for crops

TFP equations

$$TFP_{CROP(g)} = AO_{(g)}$$

$$TFP_{LIVESTOCK(y)} = AF_{("Livestock",y)} * \frac{P_{NCRPFEED(y)}X_{NCRPFEED(y)}}{P_{("Livestock",y)}Q_{("Livestock",y)}}$$

$$TFP_{PROC\_FOOD(y)} = AF_{("Proc\_Food",y)} * \frac{P_{NCRPFOOD(y)}X_{NCRPFOOD(y)}}{P_{("Proc\_Food",y)}Q_{("Proc\_Food",y)}}$$

Appendix E. SIMPLE GEMPACK Code

```
!============================================================================!
!  SIMPLE: a Simplified International Model of agricultural Prices,          !
!          Land use and the Environment                                      !
!          by U. Baldos and T. Hertel                                        !
!          Department of Agricultural Economics                              !
!          Purdue University, IN, USA                                        !
!============================================================================!
!  About this version of SIMPLE (Oct. 2013):
    This version contains the basic model framework which includes
    the demand, production & crop accounting systems.

  Short description of SIMPLE:
    SIMPLE is designed to facilitate analysis of the drivers behind the
    long run supply and demand for land in agriculture. Commodity demand,
    which is disaggregated by 5 income regions, are characterized in terms
    of an "ad hoc" demand system, wherein food and non-food commodities
    are considered. Food consists of crops, livestock and processed food
    commodities. Crop use include crops consumed as food, as feedstock in
    global biofuel production and as inputs in the livestock and
    processed food industries. Production of livestock and processed food
    which occurs in each demand region uses crop and non-crop inputs.

    The global supply of crops is based on production in 7 geographic regions,
    each with a different crop production function which combines land and
    nonland inputs to produce a homogeneous crop output. The supply of cropland
    varies by region and is a function of cropland returns in that geographic
    region, as well as land supply shifters capturing the impact of competing
    uses of land, including urbanization and environmental requirements. The
    supply of nonland inputs is more price elastic and reflects the composite
    supply of labor, capital and purchased materials to the crops sector.

    In general, production functions for livestock, processed foods and
    crops follow the constant elasticity of substitution framework.
    However, Leontiff production is imposed in the processed food industry.

    There is a single global price for crops which adjusts to equilibrate
    global supply and demand for crops. For other commodities, market
    equilibrium occurs at a regional level. As a consequence, processed
    food, livestock and non-food products have unique regional prices.

    Quantity of crops in this model are aggregated and are expressed
    in terms of corn equivalent (i.e. "normalized" quantities)

 Coverage of data used in the model:
    119 countries; 50 crop commodities

 --------------------------------------------
 Overview of SIMPLE TAB file structure
 --------------------------------------------
      I. PRELIMINARIES

     II. CONSUMER DEMAND SYSTEM
         II.A  CONSUMER DEMAND DRIVERS, VARIABLES & ELASTICITIES
           II.A.1  Exogenous Drivers of Commodity Demand
```

```
           II.A.2  Sources of Industrial Demands for Crops
           II.A.3  Variables Related to Commodity Demand
           II.A.4  Demand Elasticities [Ad hoc System]
         II.B  CROP USE ACCOUNTING SYSTEM
         II.C  CONSUMER DEMAND EQUATIONS
           II.C.1  Per Capita Commodity Demand
           II.C.2  Regional Commodity Demand

    III. PRODUCTION SYSTEM
        III.A  CROP PRODUCTION SYSTEM
          III.A.1  Coefficients & Variables Related to Crop Production
          III.A.2  Exogenous Shifters of Land Supply
          III.A.3  Coefficients & Variables Related to Land Demand/Supply
          III.A.4  Variables Related to Technical Change in Crop Production
          III.A.5  Key Equations on Land Demand/Supply & Crop Production
            III.A.5.1  Long Run Supply for Land
            III.A.5.2  Long Run Supply for Nonland Inputs
            III.A.5.3  Long Run Derived Demand for Land
            III.A.5.4  Long Run Derived Demand for Nonland Inputs
            III.A.5.5  Zero Profit Condition in the Crop Sector
        III.B. GLOBAL MARKET CLEARING EQUATIONS FOR CROPS
          III.B.1  Global Crop Price Equation
          III.B.2  Market clearing for crops across uses
        III.C  LIVESTOCK & PROCESSED FOOD PRODUCTION
          III.C.1  Coeff. & Var. Related to Livestock & Proc. Food Prod.
          III.C.2  Var. Related to Tech. Chg. in Lvstck & Proc. Food Prod.
          III.C.3  Key Equations in Livestock & Proc. Food Production
            III.C.3.1  Long Run Derived Dmd for Feed inputs
            III.C.3.2  Long Run Derived Dmd for Nonfeed Inputs
            III.C.3.3  Long Run Derived Dmd for Crop inputs in Proc. Food
            III.C.3.4  Long Run Drvd Dmd for Noncrop inputs used in Proc. Food
            III.C.3.5  Zero Profit Condition in the Livestock Sector
            III.C.3.6  Zero Profit Condition in the Proc. Food Sector

      V. APPPENDICIES
         Appendix A. Checks in the model
         Appendix B. Summary Statistics
!
!<  I. PRELIMINARIES
    ====================================================================   >!
!   Declaration of files & sets                                             !
File LANDDATA # base data file (see 'in' folder) #;
     LANDPARM # parameter file (see 'in' folder) #;
     LANDSETS # set file       (see 'in' folder) #;

Set REG_INC    # Regions by income group #
                  read elements from file LANDSETS header "H1";
    REG_GEO    # Regions by geographic location #
                   read elements from file LANDSETS header "H2";
    CONS_COMM  # commodities for consumption #
                  read elements from file LANDSETS header "AGGC";
    FOOD_COMM  # food commodities: subset of CONS_COMM #
                  read elements from file LANDSETS header "AGGF";
                  subset FOOD_COMM is subset of CONS_COMM;
Set NFOOD_COMM # nonfood commodity: subset of CONS_COMM #
                  = CONS_COMM - FOOD_COMM;
Set COEF       # regression parameters (i.e. intercept, slope) #
                  read elements from file LANDSETS header "COEF";
```

```
!   Declaration of slack variables (for advanced users only).                !
Variable (all,i,CONS_COMM) (all,y,REG_INC)                   slack_q_pc(i,y)
    # slack variable for fixing per capita demand #;
Variable (all,g,REG_GEO)                                     slack_pnland(g)
    # slack variable for fixing nonland input price #;
Variable                                                     slack_acrpuse
    # slack variable for targeting global price from demand side # ;
Variable (all,y,REG_INC)                                     slack_crpfeed(y)
    # slack variable for allowing targeting of p_AFCRPFEED(y) # ;
Variable (all,y,REG_INC)                                     slack_crpfood(y)
    # slack variable for allowing targeting of p_AFCRPFOOD(y) # ;

!<  II. CONSUMER DEMAND SYSTEM
    ====================================================================   >!
!   II.A  CONSUMER DEMAND DRIVERS, VARIABLES & ELASTICITIES
    --------------------------------------------------------------------   >!
!   II.A.1  Exogenous Drivers of Commodity Demand
    *************************************************************           !
Variable (levels) (all,y,REG_INC)                            INC_PC(y)
    # per capita income (in constant 2000 USD) #;
Variable (levels) (all,y,REG_INC)                            POP(y)
    # population (in million) #;

!   II.A.2  Sources of Industrial Demands for Crops
    *************************************************************           !
! (in million MTs) !
Variable (levels)                                            QCRPBIOF
    # global crop demand for biofuel use  #;
Variable (levels) (all,y,REG_INC)                            QCRPFEED(y)
    # feed use in livestock production #;
Variable (levels) (all,y,REG_INC)                            QCRPFOOD(y)
    # crops use in processed food production #;

!   II.A.3  Variables Related to Commodity Demand
    *************************************************************           !
!         price & quantity variables                                        !
Variable (levels) (all,i,CONS_COMM)(all,y,REG_INC)           P(i,y)
   # commodity prices (in USD per unit) #;
Variable (levels) (all,i,CONS_COMM)(all,y,REG_INC)           QPC(i,y)
   # per capita commodity consumption #
     !(in MTs qty. or USD) !;
Variable (levels) (all,i,CONS_COMM)(all,y,REG_INC)           QCONS(i,y)
   # regional commodity consumption #
     !(in M MTs qty. or M USD) !;
Variable (levels) (all,i,CONS_COMM)(all,y,REG_INC)           VCONS(i,y)
   # value of regional commodity consumption #
     !(in M USD) !;

     Read QCONS  from file LANDDATA header "QCON";
          VCONS  from file LANDDATA header "VCON";
          INC_PC from file LANDDATA header "YPC";
          POP    from file LANDDATA header "POP";

!         Formulas for deriving prices & per capita consumption             !
     Formula (initial) (all,i,CONS_COMM)(all,y,REG_INC)      QPC(i,y)
     = QCONS(i,y) / POP(y) ;
     Formula (initial) (all,i,CONS_COMM)(all,y,REG_INC)      P(i,y)
```

```
     = VCONS(i,y) / QCONS(i,y) ;

!   II.A.4  Demand Elasticities [Ad hoc System]
    *************************************************************           !
!        Parameters from regression of the demand elasticities   !
Coefficient (parameter) (all,i,CONS_COMM) (all,k,COEF)      EIY(i,k)
    # regression estimates of income elas. & per capita incomes #;
Coefficient (parameter) (all,i,CONS_COMM) (all,k,COEF)      EIP(i,k)
    # regression estimates of own-price elas. & per capita incomes #;
Coefficient (all,i,CONS_COMM) (all,y,REG_INC)                adhocEINC(i,y)
    # predicted income elasticities #;
Coefficient (all,i,CONS_COMM) (all,y,REG_INC)                adhocEOP(i,y)
    # predicted own-price elasticities #;
    Read EIP from file LANDPARM header "EIP";
         EIY from file LANDPARM header "EIY";

!        Actual consumption elasticities used in model equations             !
Coefficient (all,i,CONS_COMM) (all,y,REG_INC)                EINC(i,y)
    # income elasticity of demand #;
Coefficient (all,i,CONS_COMM)(all,y,REG_INC)                 EOP(i,y)
    # own-price elasticities of demand #;

!        Linkage between per capita income & the regression parameters      !
    Formula (all,i,CONS_COMM) (all,y,REG_INC)                adhocEINC(i,y)
    = EIY(i,"intercept") + EIY(i,"slope") * loge(INC_PC(y));
    Formula (all,i,CONS_COMM) (all,y,REG_INC)                adhocEOP(i,y)
    = EIP(i,"intercept") + EIP(i,"slope") * loge(INC_PC(y));

!        Linking between predicted & model equation elasticities             !
    Formula (all,i,CONS_COMM) (all,y,REG_INC)                EINC(i,y)
    = adhocEINC(i,y);
    Formula (all,i,CONS_COMM)(all,y,REG_INC)                 EOP(i,y)
    = adhocEOP(i,y);

!<  II.B  CROP USE ACCOUNTING SYSTEM
    --------------------------------------------------------------------   >!
!          Quantity of crops                                                 !
Variable (levels) (all,g,REG_GEO)                            QCROPg(g)
    # crop production (in million MTs) #;
!         Crop Allocation Shares                                             !
Coefficient (all,y,REG_INC)                                  CRPSHRCONS(y)
    # crops allocated to direct food consumption #;
Coefficient (all,y,REG_INC)                                  CRPSHRFEED(y)
    # crops allocated to the livestock sector #;
Coefficient (all,y,REG_INC)                                  CRPSHRFOOD(y)
    # crops allocated to the processed food industry  #;
Coefficient                                                  CRPSHRBIO
    # crops allocated to the global biofuel sector #;

     Read QCRPFEED from file LANDDATA header "QFD";
          QCRPFOOD from file LANDDATA header "QPR";
          QCROPg   from file LANDDATA header "QS";
          QCRPBIOF from file LANDDATA header "BIOF";

!         Formulas for calculating crop allocation shares                    !
     Formula (all,y,REG_INC)                                 CRPSHRCONS(y)
        = QCONS("Crops",y) / [sum(g, REG_INC, QCRPFEED(g)
                           + QCRPFOOD(g) + QCONS("Crops",g)) + QCRPBIOF];
```

```
     Formula (all,y,REG_INC)                                  CRPSHRFEED(y)
        = QCRPFEED(y) / [sum(g, REG_INC, QCRPFEED(g)
                           + QCRPFOOD(g) + QCONS("Crops",g)) + QCRPBIOF];
     Formula (all,y,REG_INC)                                  CRPSHRFOOD(y)
        = QCRPFOOD(y) / [sum(g, REG_INC, QCRPFEED(g)
                           + QCRPFOOD(g) + QCONS("Crops",g)) + QCRPBIOF];
     Formula                                                  CRPSHRBIO
        = 1 - sum(y, REG_INC, CRPSHRCONS(y)
                            + CRPSHRFEED(y) + CRPSHRFOOD(y));

!         Formulas for reallocating global crop supply to global demand
          to initialize the crop demand data                                 !
     Formula (initial) (all,y,REG_INC)                        QCONS("Crops",y)
        = CRPSHRCONS(y) * sum(g,REG_GEO, QCROPg(g));
     Formula (initial) (all,y,REG_INC)                        QCRPFEED(y)
        = CRPSHRFEED(y) * sum(g,REG_GEO, QCROPg(g));
     Formula (initial) (all,y,REG_INC)                        QCRPFOOD(y)
        = CRPSHRFOOD(y) *sum(g,REG_GEO, QCROPg(g));
     Formula (initial)                                        QCRPBIOF
        = CRPSHRBIO * sum(g,REG_GEO, QCROPg(g));

!<  II.C  CONSUMER DEMAND EQUATIONS
    --------------------------------------------------------------------   >!
!    II.C.1  Per Capita Commodity Demand
    **********************************************************************  !
Equation E_QPC
    # determines the endogenous price for all commodities #
    (all,i,CONS_COMM) (all,y,REG_INC)
    p_QPC(i,y) =   EOP(i,y) * p_P(i,y)
                 + EINC(i,y) * p_INC_PC(y) + slack_q_pc(i,y);
!    II.C.2  Regional Commodity Demand
    **********************************************************************  !
Equation E_CONS
    # determines the change in regional consumption of all commodities #
    (all,i,CONS_COMM)(all,y,REG_INC)
    p_QCONS(i,y) = p_QPC(i,y) + p_POP(y) ;

!         Equation of value of commodity consumption                         !
     Equation E_VCONS  (all,i,CONS_COMM)(all,y,REG_INC)      p_VCONS(i,y)
     = p_P(i,y) + p_QCONS(i,y);

!<  III. PRODUCTION SYSTEM
    ====================================================================   >!
!<  III.A  CROP PRODUCTION SYSTEM
   --------------------------------------------------------------------    >!
!   III.A.1  Coefficients & Variables Related to Crop Production
    ****************************************************************        !
!          Elasticity of substitution between land & nonland inputs          !
Coefficient (Parameter) (all,g,REG_GEO)                       ECROP(g)
    # elasticity of substitution in production of crops #;

!          Value and price of crops                                          !
Variable (levels) (all,g,REG_GEO)                             VCROPg(g)
    # value of crop production (in M USD) #;
Variable (levels)                                             PCROP
    # world crop price in USD per tonne (in USD) #;

!   III.A.2  Exogenous Shifters of Land Supply
```

```
    ****************************************************************        !
Variable (levels) (all,g,REG_GEO)                            QURBLANDg(g)
    # Supply shifter: land demand due to urbanization (in 1000s hectares) #;
Variable (levels) (all,g,REG_GEO)                            QENVLANDg(g)
    # Supply shifter: land demand for envtl. services (in 1000s hectares) #;
    ![[!  Not yet implemented in this version !]]!

!   III.A.3  Coefficients & Variables Related to Land Demand/Supply
    ****************************************************************        !
!          Price elasticities of land & nonland factors                     !
Coefficient (Parameter) (all,g,REG_GEO)                      ELANDg(g)
    # price elas. of land supply with respect to land rents #;
Coefficient (Parameter) (all,g,REG_GEO)                      ENLANDg(g)
    # price elas. of nonland supply with respect to nonland returns #;

!          Cost share of nonland & land inputs                              !
Coefficient (all,g,REG_GEO)                                  SHRLANDg(g)
    # cost share of land inputs in crop production #;
Coefficient (all,g,REG_GEO)                                  SHRNLANDg(g)
    # cost share of nonland inputs in crop production #;

!          Cropland conversion factors                                      !
Coefficient (Parameter) (all,g,REG_GEO)                      LCFURBg(g)
    # land conversion factor from urban land to cropland #;
Coefficient (all,g,REG_GEO)                                  URB2QLANDg(g)
    # ratio of urban lands to croplands #;
Coefficient (Parameter) (all,g,REG_GEO)                      LCFENVg(g)
    # land conversion factor from land in envtl. services to cropland #;
    ![[!  Not yet implemented in this version !]]!

!          Values, quantities and prices of land & nonland inputs
           used in crop production                                          !
Variable (levels) (all,g,REG_GEO)                            QLANDg(g)
    # Arable land & permanent croplands (in 1000s hectares) #;
Variable (levels) (all,g,REG_GEO)                            VLANDg(g)
    # Value of land inputs (in M USD) #;
Variable (levels) (all,g,REG_GEO)                            PLANDg(g)
    # Land rents (in 1000 USD per hectare) #;
Variable (levels) (all,g,REG_GEO)                            QNLANDg(g)
    # Nonland inputs (in M USD) #;
Variable (levels) (all,g,REG_GEO)                            VNLANDg(g)
    # Nonland inputs (in M USD) #;
Variable (levels) (all,g,REG_GEO)                            PNLANDg(g)
    # Price index of nonland inputs #;

!          Regional crop yields                                             !
Variable (levels) (all,g,REG_GEO)                            YIELDg(g)
    # crop yields (in 1000s MTs per hectare) #;

     Read QLANDg      from file LANDDATA header "QLD";
          VLANDg      from file LANDDATA header "VLD";
          QNLANDg     from file LANDDATA header "QNLD";
          PNLANDg     from file LANDDATA header "PNLD";
          QURBLANDg   from file LANDDATA header "QURB";
          QENVLANDg   from file LANDDATA header "QENV";
          ELANDg      from file LANDPARM header "ELN";
          ENLANDg     from file LANDPARM header "ENLN";
          LCFURBg     from file LANDPARM header "LURB";
```

```
          LCFENVg     from file LANDPARM header "LENV";
          ECROP       from file LANDPARM header "ECRP";

!    Formulas and equation defining changes in the values and prices
     of land and nonland inputs                                             !
     Formula (initial) (all,g,REG_GEO)                       PLANDg(g)
          = VLANDg(g)/QLANDg(g);
     Equation E_VLANDg (all,g,REG_GEO)                       p_VLANDg(g)
          = p_PLANDg(g) + p_QLANDg(g);
     Formula & Equation E_VNLANDg (all,g,REG_GEO)            VNLANDg(g)
          = PNLANDg(g) * QNLANDg(g);

!    Formula for calculating urban to permanent cropland ratio             !
     Formula (all,g,REG_GEO)                                 URB2QLANDg(g)
          = QURBLANDg(g)/QLANDg(g);

!    Formulas for calculating the initial values of VCROP & PCROP          !
     Formula (initial) (all,g,REG_GEO)                       VCROPg(g)
         = VNLANDg(g) + VLANDg(g);
     Formula (initial)                                       PCROP
         = sum(g,REG_GEO, VCROPg(g))/sum(g,REG_GEO, QCROPg(g));

!    Formulas and equations for deriving cost shares & definition of
     yields, value & technological change                                   !
     Formula (all,g,REG_GEO)                                 SHRLANDg(g)
         = VLANDg(g) / ( VNLANDg(g) + VLANDg(g) );
     Formula (all,g,REG_GEO)                                 SHRNLANDg(g)
         = (1 - SHRLANDg(g)) ;
     Equation E_VCROPg (all,g,REG_GEO)                       p_VCROPg(g)
         = p_PCROP + p_QCROPg(g);
     Formula&Equation (levels) E_YIELDg (all,g,REG_GEO)      YIELDg(g)
         = QCROPg(g) / QLANDg(g);

!   III.A.4  Variables Related to Technical Change in Crop Production
    *****************************************************************       !
Variable (levels) (all,g,REG_GEO)                            AOCROPg(g)
    # input-neutral (Hicks-neutral) eff. index in crop production #;
Variable (levels)                                            AOCROP
    # sub-comp. of input-neutral eff. index in crop prod.: global #;
Variable (levels) (all,g,REG_GEO)                            AOCROPr(g)
    # sub-comp. of input-neutral eff. index in crop prod.: regional #;
Variable (levels) (all,g,REG_GEO)                            AOCROPr_cc(g)
    # sub-comp. of input-neutral eff. index in crop prod.: regional #;
     ! used for implementing regional climate change yield impacts !

Variable (levels) (all,g,REG_GEO)                            AFLANDg(g)
    # land-biased eff. index in crop production #;
Variable (levels)                                            AFLAND
    # sub-comp. of land-biased eff. index: global #;
Variable (levels) (all,g,REG_GEO)                            AFLANDr(g)
    # sub-comp. of land-biased eff. index: regional #;
Variable (levels) (all,g,REG_GEO)                            AFNLANDg(g)
    # nonland biased eff. index in crop production #;
Variable (levels)                                            AFNLAND
    # sub-comp. of nonland biased eff. index: global #;
Variable (levels) (all,g,REG_GEO)                            AFNLANDr(g)
    # sub-comp. of nonland biased eff. index: regional #;
```

```
!    Formulas initializing values of tech. change variables                 !
     Formula (initial) (all,g,REG_GEO)       AFLANDg(g)     = 1;
     Formula (initial)                       AFLAND         = 1;
     Formula (initial) (all,g,REG_GEO)       AFLANDr(g)     = 1;
     Formula (initial)                       AOCROP         = 1;
     Formula (initial) (all,g,REG_GEO)       AOCROPg(g)     = 1;
     Formula (initial) (all,g,REG_GEO)       AOCROPr(g)     = 1;
     Formula (initial)                       AFNLAND        = 1;
     Formula (initial) (all,g,REG_GEO)       AFNLANDg(g)    = 1;
     Formula (initial) (all,g,REG_GEO)       AFNLANDr(g)    = 1;
     Formula (initial) (all,g,REG_GEO)       AOCROPr_cc(g)  = 1;

!    Formulas linking sub-components of tech. change variables             !
     Equation E_AFNLANDg (all,g,REG_GEO)                    p_AFNLANDg(g)
     = p_AFNLANDr(g) + p_AFNLAND ;
     Equation E_AFLANDg (all,g,REG_GEO)                     p_AFLANDg(g)
     = p_AFLANDr(g) + p_AFLAND ;
     Equation E_AOCROPg (all,g,REG_GEO)                     p_AOCROPg(g)
     = p_AOCROPr(g) + p_AOCROP + p_AOCROPr_cc(g);

!<  III.A.5  Key Equations on Land Demand/Supply & Crop Production
    **************************************************************         >!
!   III.A.5.1  Long Run Supply for Land
    ----------------------------------------------------------------------  !
Equation E_PLANDg
    # determines the endogenous price of land in crop production #
    (all,g,REG_GEO)
    p_QLANDg(g) = ELANDg(g) * p_PLANDg(g)
                    - LCFURBg(g) * URB2QLANDg(g) * p_QURBLANDg(g)
                    - LCFENVg(g) * p_QENVLANDg(g);

!   III.A.5.2  Long Run Supply for Nonland Inputs
    ----------------------------------------------------------------------  !
Equation E_PNLANDg
    # determines the endogenous price of nonland inputs used in crop prod.  #
    (all,g,REG_GEO)
    p_QNLANDg(g) = ENLANDg(g) * p_PNLANDg(g) + slack_pnland(g) ;

!   III.A.5.3  Long Run Derived Demand Equation for Land
    ----------------------------------------------------------------------  !
Equation E_QLANDg
    # determines the endogenous use of croplands in crop prod. #
    (all,g,REG_GEO)
    p_QLANDg(g) + p_AFLANDg(g)  =  p_QCROPg(g) - p_AOCROPg(g)
        - ECROP(g) * [p_PLANDg(g) - p_AFLANDg(g) - p_PCROP - p_AOCROPg(g)];

!   III.A.5.4  Long Run Derived Demand Equation for Nonland Inputs
    ----------------------------------------------------------------------  !
Equation E_QNLAND
    # determines the endogenous use of nonland inputs in crop prod. #
    (all,g,REG_GEO)
    p_QNLANDg(g) + p_AFNLANDg(g)  =  p_QCROPg(g) - p_AOCROPg(g)
        - ECROP(g) * [p_PNLANDg(g) - p_AFNLANDg(g) - p_PCROP - p_AOCROPg(g)];

!   III.A.5.5  Zero Profit Condition for Crop Producers
    ----------------------------------------------------------------------  !
Equation E_QCROPg
    # determines the endogenous output of the crop sector #
```

```
    (all,g,REG_GEO)
    p_PCROP + p_AOCROPg(g) =
                       [SHRLANDg(g)] * [p_PLANDg(g) - p_AFLANDg(g)] +
                       [SHRNLANDg(g)] * [p_PNLANDg(g) - p_AFNLANDg(g)];

!<  III.B. GLOBAL MARKET CLEARING EQUATIONS FOR CROPS
   --------------------------------------------------------------------    >!
!   III.B.1  Global crop price equation
    ********************************************************************     !
Equation E_P
    # integrated global market for crops (i.e. single world price) #
    (all,y,REG_INC)
    p_P("Crops",y) = p_PCROP;

!   III.B.2  Market clearing for crops across uses
    ********************************************************************     !
Equation (levels) E_PCROP
    # global crop demand and global supply balance #
       sum(g, REG_GEO, QCRPg(g)) = sum(y,REG_INC, QCRPFEED(y)
                  + QCRPFOOD(y) + QCONS("Crops",y)) + QCRPBIOF ;

!<  III.C  LIVESTOCK & PROCESSED FOOD PRODUCTION
   --------------------------------------------------------------------    >!
!<  III.C.1  Coeff. & Var. Related to Livestock & Proc. Food Prod.
    ****************************************************************       >!
!          Prices and quantities of non-crop inputs                          !
Variable (levels) (all,y,REG_INC)                            QNCRPFEED(y)
    # quantity of non-feed inputs used in livestock production #
    ! (in M USD) ! ;
Variable (levels) (all,y,REG_INC)                            QNCRPFOOD(y)
    # quant. of non-crop inputs used in processed food production #
    ! (in M USD) !;
Variable (levels) (all,y,REG_INC)                            PNCRPFEED(y)
    # price index of non-feed inputs #;
Variable (levels) (all,y,REG_INC)                            PNCRPFOOD(y)
    # price index of non-crop inputs used in proc. food prod. #;

!         Elasticities of substitution                                       !
Coefficient (Parameter)                                      ECRPFEED
    # global elasticity of subs. in prod. of livestock #;
Coefficient (Parameter)                                      ECRPFOOD
    # global elasticity of subs. in prod. of proc. foods #;

!         Cost Shares                                                        !
Coefficient (all,y,REG_INC)                                  SHRCRPFEED(y)
    # cost share of feed inputs in the livestock industry #;
Coefficient (all,y,REG_INC)                                  SHRNCRPFEED(y)
    # cost share of non-feed inputs in the livestock industry #;
Coefficient (all,y,REG_INC)                                  SHRCRPFOOD(y)
    # cost share of crop inputs in the processed food industry #;
Coefficient (all,y,REG_INC)                                  SHRNCRPFOOD(y)
    # cost share of non-crop inputs in the processed food industry #;

    Read PNCRPFEED   from file LANDDATA header "PNF";
         PNCRPFOOD   from file LANDDATA header "PNPR";
         ECRPFEED    from file LANDPARM header "EFED";
         ECRPFOOD    from file LANDPARM header "EFOD";
```

```
!          Formulas for initializing QNCRPFEED & QNCRPFOOD                    !
     Formula (initial) (all,y,REG_INC)                            QNCRPFEED(y)
         = VCONS("Livestock",y) - QCRPFEED(y) * PCROP ;
     Formula (initial) (all,y,REG_INC)                            QNCRPFOOD(y)
         = VCONS("Proc_Food",y) - QCRPFOOD(y) * PCROP ;

!          Formulas for calculating cost shares in these sectors              !
     Formula (all,y,REG_INC)                                      SHRCRPFEED(y)
         =  QCRPFEED(y) * PCROP / VCONS("Livestock",y);
     Formula (all,y,REG_INC)                                      SHRNCRPFEED(y)
         = 1 - SHRCRPFEED(y) ;
     Formula (all,y,REG_INC)                                      SHRCRPFOOD(y)
         =  QCRPFOOD(y) * PCROP / VCONS("Proc_Food",y);
     Formula (all,y,REG_INC)                                      SHRNCRPFOOD(y)
         = 1 - SHRCRPFOOD(y) ;

!<  III.C.2  Var. Related to Tech. Chg. in Lvstck & Proc. Food Prod.
    ****************************************************************       >!
!          Technical change variables in the livestock sector           !
Variable (levels) (all,y,REG_INC)                                 AOCRPFEED(y)
    # hicks-neutral eff. index in livestock prod. #;
Variable (levels) (all,y,REG_INC)                                 AFCRPFEED(y)
    # feed efficiency index #;
Variable (levels)                                                 AFCRPFEEDy
    # sub-component of feed eff. index: global #;
Variable (levels) (all,y,REG_INC)                                 AFCRPFEEDr(y)
    # sub-component of feed eff. index: regional #;
Variable (levels) (all,y,REG_INC)                                 AFNCRPFEED(y)
    # non-feed efficiency index #;
Variable (levels)                                                 AFNCRPFEEDy
    # sub-component of the non-feed eff. index: global #;
Variable (levels) (all,y,REG_INC)                                 AFNCRPFEEDr(y)
    # sub-component of the non-feed eff. index: regional #;

!          Technical change variables in the processed food sector      !
Variable (levels) (all,y,REG_INC)                                 AOCRPFOOD(y)
    # hicks-neutral eff. index in proc. food prod. #;
Variable (levels) (all,y,REG_INC)                                 AFCRPFOOD(y)
    # crop input efficiency index in proc. food prod. #;
Variable (levels)                                                 AFCRPFOODy
    # sub-comp. of crop input eff. index: global #;
Variable (levels) (all,y,REG_INC)                                 AFCRPFOODr(y)
    # sub-comp. of crop input eff. index: regional #;
Variable (levels) (all,y,REG_INC)                                 AFNCRPFOOD(y)
    # eff. index of non-crop inputs in proc. food prod.#;
Variable (levels)                                                 AFNCRPFOODy
    # sub-comp. of the non-crop eff. index: global #;
Variable (levels) (all,y,REG_INC)                                 AFNCRPFOODr(y)
    # sub-comp. of the non-crop eff. index: regional #;

!          Formulas initializing values of tech. change variables             !
     Formula (initial) (all,y,REG_INC)    AOCRPFEED(y)   = 1;
     Formula (initial) (all,y,REG_INC)    AOCRPFOOD(y)   = 1;
     Formula (initial) (all,y,REG_INC)    AFCRPFEED(y)   = 1;
     Formula (initial) (all,y,REG_INC)    AFCRPFOOD(y)   = 1;
     Formula (initial) (all,y,REG_INC)    AFNCRPFEED(y)  = 1;
     Formula (initial) (all,y,REG_INC)    AFNCRPFOOD(y)  = 1;
     Formula (initial)                    AFCRPFEEDy     = 1;
```

```
     Formula (initial)                    AFCRPFOODy     = 1;
     Formula (initial)                    AFNCRPFEEDy    = 1;
     Formula (initial)                    AFNCRPFOODy    = 1;
     Formula (initial) (all,y,REG_INC)    AFCRPFEEDr(y)  = 1;
     Formula (initial) (all,y,REG_INC)    AFCRPFOODr(y)  = 1;
     Formula (initial) (all,y,REG_INC)    AFNCRPFEEDr(y) = 1;
     Formula (initial) (all,y,REG_INC)    AFNCRPFOODr(y) = 1;

!    Formulas linking sub-components of tech. change variables             !
     Equation E_AFNCRPFEED (all,y,REG_INC)                   p_AFNCRPFEED(y)
        = p_AFNCRPFEEDy + p_AFNCRPFEEDr(y);
     Equation E_AFNCRPFOOD (all,y,REG_INC)                   p_AFNCRPFOOD(y)
        = p_AFNCRPFOODy + p_AFNCRPFOODr(y);
     Equation E_AFCRPFEED (all,y,REG_INC)                    p_AFCRPFEED(y)
        = p_AFCRPFEEDy + p_AFCRPFEEDr(y);
     Equation E_AFCRPFOOD (all,y,REG_INC)                    p_AFCRPFOOD(y)
        = p_AFCRPFOODy + p_AFCRPFOODr(y);

!<  III.C.3  Key Equations in Livestock & Proc. Food Production
    ****************************************************************       >!
!   III.C.3.1  Long Run Derived Demand for Feed inputs
    --------------------------------------------------------------------    !
Equation E_QCRPFEED
    # determines the endogenous use of feed in livestock production #
    (all,y,REG_INC)
    p_QCRPFEED(y) + p_AFCRPFEED(y) =
        p_QCONS("Livestock",y) - p_AOCRPFEED(y)
        - ECRPFEED * [p_P("Crops",y) - p_AFCRPFEED(y)
        - p_P("Livestock",y) - p_AOCRPFEED(y)];

!   III.C.3.2  Long Run Derived Demand for Nonfeed Inputs
    --------------------------------------------------------------------    !
Equation E_QNCRPFEED
    # determines the endogenous use of nonfeed in livestock production #
    (all,y,REG_INC)
    p_QNCRPFEED(y) + p_AFNCRPFEED(y) =
      p_QCONS("Livestock",y) - p_AOCRPFEED(y)
       - ECRPFEED * [p_PNCRPFEED(y) - p_AFNCRPFEED(y)
       - p_P("Livestock",y) - p_AOCRPFEED(y)];

!   III.C.3.3  Long Run Derived Demand for Crop inputs in Proc. Food
    --------------------------------------------------------------------    !
Equation E_QCRPFOOD
    # determines the endogenous use of crop inputs in proc. food #
    (all,y,REG_INC)
    p_QCRPFOOD(y) + p_AFCRPFOOD(y)  =
        p_QCONS("Proc_Food",y) - p_AOCRPFOOD(y)
         - ECRPFOOD * [p_P("Crops",y) - p_AFCRPFOOD(y)
         - p_P("Proc_Food",y) - p_AOCRPFOOD(y)];

!   III.C.3.4  Long Run Derived Demand for Noncrop inputs used in Proc. Food
    --------------------------------------------------------------------    !
Equation E_QNCRPFOOD
    # determines the endogenous use of non-crop inputs in proc. food #
    (all,y,REG_INC)
    p_QNCRPFOOD(y) + p_AFNCRPFOOD(y)  =
      p_QCONS("Proc_Food",y) - p_AOCRPFOOD(y)
       - ECRPFOOD * [p_PNCRPFOOD(y) - p_AFNCRPFOOD(y)
```

```
       - p_P("Proc_Food",y) - p_AOCRPFOOD(y)];

!   III.C.3.5  Zero Profit Condition for Livestock Producers
    --------------------------------------------------------------------    !
Equation E_QCONS_LIVESTOCK
    # determines the endogenous output of the livestock sector #
    !   (i.e. market clearing condition in each income region )!
    (all,y,REG_INC)
     p_P("Livestock",y) + p_AOCRPFEED(y) =
               [SHRCRPFEED(y)] * [p_P("Crops",y) - p_AFCRPFEED(y)] +
               [SHRNCRPFEED(y)] * [p_PNCRPFEED(y) - p_AFNCRPFEED(y)];

!   III.C.3.6  Zero Profit Condition for Processed Foods Producers
    --------------------------------------------------------------------    !
Equation E_QCONS_PRCFOOD
    # determines the endogenous output of the processed food sector #
    !   (i.e. market clearing condition in each income region )!
    (all,y,REG_INC)
    p_P("Proc_Food",y) + p_AOCRPFOOD(y) =
                  [SHRCRPFOOD(y)] * [p_P("Crops",y) - p_AFCRPFOOD(y)] +
                 [SHRNCRPFOOD(y)] * [p_PNCRPFOOD(y) - p_AFNCRPFOOD(y)];

!   Option to endo. tech chg. in lvstck & proc. food (for advanced users)
    --------------------------------------------------------------------    !
!<  In order to target commodity price from the demand side, we can swap
    crpfeedslack with p_AFCRPFEED and similarly for food, then acrpuse
    becomes an instrument for targeting price.                            >!

   Equation E_AFCRPFEED_slack
    # endogenizes tech change in the livestock industry #
    (all,y,REG_INC)                                           p_AFCRPFEED(y)
    = slack_acrpuse + slack_crpfeed(y) ;

   Equation E_AFCRPFOOD_slack
    # endogenizes tech change in the processed food industry #
    (all,y,REG_INC)                                          p_AFCRPFOOD(y)
    = slack_acrpuse + slack_crpfood(y) ;

!<  V. APPPENDICIES
    ====================================================================== >!
!<  Appendix A. Data checks in the model
    ********************************************************************** >!
Coefficient                                                      QCROPCHK
   # Clearing of crop demand & supply - should be near 0 #;
   Formula                                                       QCROPCHK
   = - sum(g, REG_GEO, QCROPg(g)) +  sum(y,REG_INC, QCRPFEED(y)
                  + QCRPFOOD(y) + QCONS("Crops",y)) + QCRPBIOF;
Coefficient (all,g,REG_GEO)                                      VCROPCHK(g)
    # Zero profit condition for crop sector - should be near 0 #;
    Formula (all,g,REG_GEO)                                      VCROPCHK(g)
    = VCROPg(g) - [VLANDg(g) + PNLANDg(g) * QNLANDg(g)];
Coefficient (all,y,REG_INC)                                      VLVSTCKCHK(y)
    # Zero profit condition for livestock sector - should be near 0 #;
    Formula (all,y,REG_INC)                                      VLVSTCKCHK(y)
    = VCONS("Livestock",y)
      - [QCRPFEED(y) * PCROP + QNCRPFEED(y) * PNCRPFEED(y)];
Coefficient (all,y,REG_INC)                                      VPRCFCHK(y)
    # Zero profit condition for proc. food sector - should be near 0 #;
```

```
    Formula (all,y,REG_INC)                                      VPRCFCHK(y)
    = VCONS("Proc_Food",y)
     - [QCRPFOOD(y) * PCROP + QNCRPFOOD(y) * PNCRPFOOD(y)];

!<  Appendix B. Summary Statistics
    ********************************************************************** >!
!             Total Factor Productivity Indices                            !
!                       Crop Sector                                        !
Variable (levels) (all,g,REG_GEO)                            TFP_CROP(g)
     # TFP for crop sector (regional) #;
     Formula&Equation (levels) E_TFP_CROP (all,g,REG_GEO)    TFP_CROP(g)
     = AOCROPg(g) * [({VLANDg(g)}/ {VCROPg(g)})
       * AFLANDg(g) + ({PNLANDg(g) * QNLANDg(g)}
       / {VCROPg(g)}) * AFNLANDg(g)];
Variable (levels)                                            TFP_CROPW
     # TFP for crop sector (global) #;
     Formula&Equation (levels) E_TFP_CROPW                   TFP_CROPW
     = sum(g, REG_GEO, [VCROPg(g)/sum(k, REG_GEO, VCROPg(k))] * TFP_CROP(g));

!                       Livestock Sector                                   !
Variable (levels) (all,y,REG_INC)                            TFP_LVSTOCK(y)
     # TFP for livestock sectors (regional) #;
     Formula&Equation (levels) E_TFP_LVSTOCK (all,y,REG_INC) TFP_LVSTOCK(y)
     = AOCRPFEED(y) * [({PCROP * QCRPFEED(y)}
       /{VCONS("livestock",y)}) * AFCRPFEED(y) + ({PNCRPFEED(y)
       * QNCRPFEED(y)}/{VCONS("livestock",y)}) * AFNCRPFEED(y)];
Variable (levels)                                            TFP_LVSTOCKW
     # TFP for livestock sectors (global) #;
     Formula&Equation (levels) E_TFP_LVSTOCKW                TFP_LVSTOCKW
     = sum(y, REG_INC, [VCONS("livestock",y)
            /sum(k, REG_INC, VCONS("livestock",k))]
            * TFP_LVSTOCK(y));

!                       Processed Food Sector                             !
Variable (levels) (all,y,REG_INC)                            TFP_PROC_FD(y)
     # TFP for proc. food sectors (regional) #;
     Formula&Equation (levels) E_TFP_PROC_FD (all,y,REG_INC) TFP_PROC_FD(y)
     = AOCRPFOOD(y) * [({PCROP * QCRPFOOD(y)}/
          {VCONS("proc_food",y)}) * AFCRPFOOD(y) + ({PNCRPFOOD(y)
          * QNCRPFOOD(y)}/{VCONS("proc_food",y)}) * AFNCRPFOOD(y)];
Variable (levels)                                            TFP_PROC_FDW
     # TFP for proc. food sectors (global) #;
     Formula&Equation (levels) E_TFP_PROC_FDW                TFP_PROC_FDW
     = sum(y, REG_INC, [VCONS("Proc_Food",y)
            /sum(k, REG_INC, VCONS("Proc_Food",k))]
            * TFP_PROC_FD(y));

!                       Key statistics computed at the global level      !
Variable (levels)                                            YIELDW
    # crop yields (global) #;
    Formula&Equation (levels) E_YIELDW                       YIELDW
    = sum(g,REG_GEO, QCROPg(g))/sum(g,REG_GEO, QLANDg(g));

Variable (levels)                                            QLANDW
    # cropland use (global) #;
    Formula&Equation (levels) E_QLANDW                       QLANDW
    = sum(g,REG_GEO, QLANDg(g));
```

```
Variable (levels)                                            PLANDW
    # land rent (global) #;
    Formula&Equation (levels) E_PLANDW                       PLANDW
    = sum(g,REG_GEO, VLANDg(g))/sum(g,REG_GEO, QLANDg(g));

Variable (levels)                                            QCROPW
    # crop production (global) #;
    Formula&Equation (levels) E_QCROPW                       QCROPW
    = sum(g,REG_GEO, QCROPg(g));

Variable (levels)                                            QNLANDW
    # Nonland inputs use (global) #;
    Formula&Equation (levels) E_QNLANDW                      QNLANDW
    = sum(g,REG_GEO, QNLANDg(g));

Variable (levels)                                            PNLANDW
    # Nonland price (global) #;
    Formula&Equation (levels) E_PNLANDW                      PNLANDW
    =  sum(g,REG_GEO, PNLANDg(g)*QNLANDg(g))
      /sum(g,REG_GEO, QNLANDg(g));

Variable (levels) (all,i,CONS_COMM)                          QCONSW(i)
    # Comm. consumption (global) #;
    Formula&Equation (levels) E_QCONSW (all,i,CONS_COMM)     QCONSW(i)
    = sum(y,REG_INC, QCONS(i,y));

Variable (levels)                                            QCRPFEEDW
    # Feed use (global) #;
    Formula&Equation (levels) E_QCRPFEEDW                    QCRPFEEDW
    = sum(y,REG_INC, QCRPFEED(y));

Variable (levels)                                            QNCRPFEEDW
    # Nonfeed use (global) #;
Formula&Equation (levels) E_QNCRPFEEDW                       QNCRPFEEDW
    = sum(y,REG_INC, QNCRPFEED(y));

Variable (levels)                                            QCRPFOODW
    # Crop input use in proc. food. sector (global) #;
Formula&Equation (levels) E_QCRPFOODW                        QCRPFOODW
    = sum(y,REG_INC, QCRPFOOD(y));

Variable (levels)                                            QNCRPFOODW
    # Noncrop input use in proc. food. sector (global) #;
Formula&Equation (levels) E_QNCRPFOODW                       QNCRPFOODW
    = sum(y,REG_INC, QNCRPFOOD(y));
```

Appendix F. Model Variables at the Base Year: 2001

Crop Production Data	Crop Output	Value of Land	Croplands	Non-land	Price of Non-land
East Asia & Pacific	1722	32856	265241	149676	1.00
Europe & Central Asia	1251	34478	350493	98128	1.00
Latin America & Caribbean	689	6573	155009	66461	1.00
Middle East & North Africa	200	3816	49368	17384	1.00
North America	717	19761	230211	56241	1.00
South Asia	838	15989	205137	72839	1.00
Sub-Saharan Africa	361	3444	144979	34822	1.00
Units	million Mt.	million USD	thou. Ha.	million USD	Index(2001)=1

Livestock Production Data	Feed	Non-Feed	Price of Non-Feed
Upper high	457	1320324	1.00
Lower high	2	3595	1.00
Upper middle	102	143402	1.00
Lower middle	379	212636	1.00
Low	86	28765	1.00
Units	million Mt.	million USD	Index(2001)=1

Processed Food Production Data	Crop inputs	Non-Crop	Price of Non-Crops
Upper high	579	654547	1.00
Lower high	2	1625	1.00
Upper middle	465	231879	1.00
Lower middle	620	196061	1.00
Low	582	236728	1.00
Units	million Mt.	million USD	Index(2001)=1

Value of Consumption	Crops	Livestock	Processed Food	Non Food
Upper high	47318	1368779	715915	22144970
Lower high	355	3855	1794	102908
Upper middle	15210	154221	281178	1768666
Lower middle	117193	252802	261788	1322221
Low	80711	37853	298465	558426
Units	million USD			

Quantity of Consumption	Crops	Livestock	Processed Food	Non Food
Upper high	446	1226521	676532	21937334
Lower high	3	3650	1586	101371
Upper middle	143	139037	243646	1692069
Lower middle	1106	222645	222594	1224559
Low	761	32403	227299	507690
Units	million Mt.	million USD		

Other Data	Income	Population	Crop use in Biofuels
Upper high	28705	856	
Lower high	17051	9	
Upper middle	4933	494	
Lower middle	1446	2090	
Low	472	2142	
Global			43
Units	USD per capita	millions	million Mt.

Appendix G. Model Parameters

Elasticities of substitution	2001 to 2006	1961 to 2006
Livestock	1.16	
Processed Food	0	
Crops	0.55	
Non-land supply response	0.49	1.34
Land supply response		
East Asia & Pacific	0.04	0.11
Europe & Central Asia	0.04	0.11
Latin America & Caribbean	0.20	0.55
Middle East & North Africa	0.11	0.29
North America	0.04	0.11
South Asia	0.10	0.28
Sub-Saharan Africa	0.20	0.55
Income elasticities		
Regression Intercept		
Crops	0.88	
Livestock	1.05	
Processed Foods	1.20	
Non-Food	1.56	
Regression Slope		
Crops	-0.10	
Livestock	-0.09	
Processed Foods	-0.10	
Non-Food	-0.05	
Price elasticities		
Regression Intercept		
Crops	-0.74	
Livestock	-0.83	
Processed Foods	-1.17	
Non-Food	-1.14	
Regression Slope		
Crops	0.07	
Livestock	0.05	
Processed Foods	0.08	
Non-Food	0.04	

Appendix H. Country Mapping in SIMPLE

FAO Code	WDI Code	UN-POP Code	Country	Region Name	SIMPLE v2 Region Code (n=154)	SIMPLE v1 Region Code (n=111)
3	ALB	8	Albania	Eastern Europe	E_Euro	Low_middle
4	DZA	12	Algeria	North Africa	N_Afr	Low_middle
7	AGO	24	Angola	Rest of Africa	RoAfr	NA
9	ARG	32	Argentina	South America	S_Amer	Up_middle
1	ARM	51	Armenia	Eastern Europe	E_Euro	Low
10	AUS	36	Australia	Australia/New Zealand	AUS_NZ	Up_higher
11	AUT	40	Austria	European Union+	EU	Up_higher
52	AZE	31	Azerbaijan	Eastern Europe	E_Euro	Low
16	BGD	50	Bangladesh	South Asia	S_Asia	Low
57	BLR	112	Belarus	Eastern Europe	E_Euro	Low_middle
23	BLZ	84	Belize	Central America & the Caribbean	CC_Amer	Low_middle
53	BEN	204	Benin	Rest of Africa	RoAfr	NA
18	BTN	64	Bhutan	South Asia	S_Asia	NA
19	BOL	68	Bolivia	South America	S_Amer	Low_middle
20	BWA	72	Botswana	Southern Africa	S_Afr	NA
21	BRA	76	Brazil	South America	S_Amer	Up_middle
27	BGR	100	Bulgaria	European Union+	EU	Low_middle
233	BFA	854	Burkina Faso	Rest of Africa	RoAfr	NA
29	BDI	108	Burundi	Rest of Africa	RoAfr	Low
115	KHM	116	Cambodia	Southeast Asia	SE_Asia	Low
32	CMR	120	Cameroon	Rest of Africa	RoAfr	Low
33	CAN	124	Canada	Canada/US	CAN_US	Up_higher
37	CAF	140	Central African Republic	Rest of Africa	RoAfr	NA
39	TCD	148	Chad	Rest of Africa	RoAfr	NA
40	CHL	152	Chile	South America	S_Amer	Up_middle
351	CHN	156	China	China/Mongolia	CHN_MNG	Low_middle
44	COL	170	Colombia	South America	S_Amer	Low_middle
45	COM	174	Comoros	Rest of Africa	RoAfr	NA
46	COG	178	Congo Rep.	Rest of Africa	RoAfr	Low
250	ZAR	180	Congo, DR	Rest of Africa	RoAfr	NA
48	CRI	188	Costa Rica	Central America & the Caribbean	CC_Amer	Up_middle
107	CIV	384	Côte d'Ivoire	Rest of Africa	RoAfr	Low
49	CUB	192	Cuba	Central America & the Caribbean	CC_Amer	NA
50	CYP	196	Cyprus	European Union+	EU	Low_higher
54	DNK	208	Denmark	European Union+	EU	Up_higher
56	DOM	214	Dominican Republic	Central America & the Caribbean	CC_Amer	Low_middle
58	ECU	218	Ecuador	South America	S_Amer	Low_middle
59	EGY	818	Egypt	North Africa	N_Afr	Low_middle
60	SLV	222	El Salvador	Central America & the Caribbean	CC_Amer	Low_middle
61	GNQ	226	Equatorial Guinea	Rest of Africa	RoAfr	NA
178	ERI	232	Eritrea	Rest of Africa	RoAfr	NA
63	EST	233	Estonia	European Union+	EU	Up_middle
238	ETH	231	Ethiopia	Rest of Africa	RoAfr	Low
66	FJI	242	Fiji	Southeast Asia	SE_Asia	Low_middle
67	FIN	246	Finland	European Union+	EU	Up_higher
68	FRA	250	France	European Union+	EU	Up_higher
74	GAB	266	Gabon	Rest of Africa	RoAfr	NA
75	GMB	270	Gambia	Rest of Africa	RoAfr	Low
73	GEO	268	Georgia	Eastern Europe	E_Euro	Low
79	DEU	276	Germany	European Union+	EU	Up_higher
81	GHA	288	Ghana	Rest of Africa	RoAfr	Low
84	GRC	300	Greece	European Union+	EU	Up_higher
89	GTM	320	Guatemala	Central America & the Caribbean	CC_Amer	NA

FAO Code	WDI Code	UN-POP Code	Country	Region Name	SIMPLE v2 Region Code (n=154)	SIMPLE v1 Region Code (n=111)
90	GIN	324	Guinea	Rest of Africa	RoAfr	Low
175	GNB	624	Guinea-Bissau	Rest of Africa	RoAfr	Low
91	GUY	328	Guyana	Central America & the Caribbean	CC_Amer	NA
93	HTI	332	Haiti	Central America & the Caribbean	CC_Amer	NA
95	HND	340	Honduras	Central America & the Caribbean	CC_Amer	Low_middle
97	HUN	348	Hungary	European Union+	EU	Up_middle
99	ISL	352	Iceland	European Union+	EU	NA
100	IND	356	India	South Asia	S_Asia	Low
101	IDN	360	Indonesia	Southeast Asia	SE_Asia	Low
102	IRN	364	Iran	Middle East	M_East	Low_middle
103	IRQ	368	Iraq	Middle East	M_East	NA
104	IRL	372	Ireland	European Union+	EU	Up_higher
105	ISR	376	Israel	Middle East	M_East	Low_higher
106	ITA	380	Italy	European Union+	EU	Up_higher
110	JPN	392	Japan	Japan/Korea	JPN_KR	Up_higher
112	JOR	400	Jordan	Middle East	M_East	Low_middle
108	KAZ	398	Kazakhstan	Eastern Europe	E_Euro	Low_middle
114	KEN	404	Kenya	Rest of Africa	RoAfr	Low
117	KOR	410	Korea, Republic	Japan/Korea	JPN_KR	NA
113	KGZ	417	Kyrgyzstan	Central Asia	C_Asia	Low
120	LAO	418	Laos	Southeast Asia	SE_Asia	Low
119	LVA	428	Latvia	European Union+	EU	Up_middle
121	LBN	422	Lebanon	Middle East	M_East	Up_middle
122	LSO	426	Lesotho	Southern Africa	S_Afr	NA
123	LBR	430	Liberia	Rest of Africa	RoAfr	NA
124	LBY	434	Libya	North Africa	N_Afr	NA
126	LTU	440	Lithuania	European Union+	EU	Up_middle
129	MDG	450	Madagascar	Rest of Africa	RoAfr	Low
130	MWI	454	Malawi	Rest of Africa	RoAfr	Low
131	MYS	458	Malaysia	Southeast Asia	SE_Asia	Up_middle
133	MLI	466	Mali	Rest of Africa	RoAfr	Low
136	MRT	478	Mauritania	Rest of Africa	RoAfr	NA
137	MUS	480	Mauritius	Southern Africa	S_Afr	Up_middle
138	MEX	484	Mexico	Central America & the Caribbean	CC_Amer	Up_middle
146	MDA	498	Moldova	Eastern Europe	E_Euro	NA
141	MNG	496	Mongolia	China/Mongolia	CHN_MNG	Low
143	MAR	504	Morocco	North Africa	N_Afr	Low_middle
144	MOZ	508	Mozambique	Rest of Africa	RoAfr	Low
147	NAM	516	Namibia	Southern Africa	S_Afr	Low_middle
149	NPL	524	Nepal	South Asia	S_Asia	Low
150	NLD	528	Netherlands	European Union+	EU	Up_higher
156	NZL	554	New Zealand	Australia/New Zealand	AUS_NZ	Up_higher
157	NIC	558	Nicaragua	Central America & the Caribbean	CC_Amer	Low
158	NER	562	Niger	Rest of Africa	RoAfr	Low
159	NGA	566	Nigeria	Rest of Africa	RoAfr	Low
162	NOR	578	Norway	European Union+	EU	Up_higher
221	OMN	512	Oman	Middle East	M_East	NA
165	PAK	586	Pakistan	South Asia	S_Asia	Low
166	PAN	591	Panama	Central America & the Caribbean	CC_Amer	Up_middle
168	PNG	598	Papua New Guinea	Southeast Asia	SE_Asia	NA
169	PRY	600	Paraguay	South America	S_Amer	Low_middle
170	PER	604	Peru	South America	S_Amer	Low_middle
171	PHL	608	Philippines	Southeast Asia	SE_Asia	Low_middle
173	POL	616	Poland	European Union+	EU	Up_middle
174	PRT	620	Portugal	European Union+	EU	Up_higher

FAO Code	WDI Code	UN-POP Code	Country	Region Name	SIMPLE v2 Region Code (n=154)	SIMPLE v1 Region Code (n=111)
177	PRI	630	Puerto Rico	Central America & the Caribbean	CC_Amer	NA
183	ROM	642	Romania	Eastern Europe	E_Euro	Low_middle
185	RUS	643	Russian Federation	Eastern Europe	E_Euro	Low_middle
184	RWA	646	Rwanda	Rest of Africa	RoAfr	NA
194	SAU	682	Saudi Arabia	Middle East	M_East	Up_middle
195	SEN	686	Senegal	Rest of Africa	RoAfr	NA
197	SLE	694	Sierra Leone	Rest of Africa	RoAfr	NA
25	SLB	90	Solomon Islands	Southeast Asia	SE_Asia	NA
202	ZAF	710	South Africa	Southern Africa	S_Afr	Low_middle
203	ESP	724	Spain	European Union+	EU	Up_higher
38	LKA	144	Sri Lanka	South Asia	S_Asia	Low_middle
207	SUR	740	Suriname	Central America & the Caribbean	CC_Amer	Low_middle
209	SWZ	748	Swaziland	Southern Africa	S_Afr	NA
210	SWE	752	Sweden	European Union+	EU	Up_higher
211	CHE	756	Switzerland	European Union+	EU	Up_higher
212	SYR	760	Syria	Middle East	M_East	NA
208	TJK	762	Tajikistan	Central Asia	C_Asia	Low
215	TZA	834	Tanzania	Rest of Africa	RoAfr	NA
216	THA	764	Thailand	Southeast Asia	SE_Asia	Low_middle
176	TMP	626	Timor Leste	Southeast Asia	SE_Asia	NA
217	TGO	768	Togo	Rest of Africa	RoAfr	Low
220	TTO	780	Trinidad and Tobago	Central America & the Caribbean	CC_Amer	Up_middle
222	TUN	788	Tunisia	North Africa	N_Afr	Low
223	TUR	792	Turkey	Middle East	M_East	Low_middle
213	TKM	795	Turkmenistan	Central Asia	C_Asia	Low_middle
226	UGA	800	Uganda	Rest of Africa	RoAfr	NA
230	UKR	804	Ukraine	Eastern Europe	E_Euro	Low
225	ARE	784	United Arab Emirates	Middle East	M_East	NA
229	GBR	826	United Kingdom	European Union+	EU	Up_higher
231	USA	850	United States	Canada/US	CAN_US	Up_higher
234	URY	858	Uruguay	South America	S_Amer	Up_middle
235	UZB	860	Uzbekistan	Central Asia	C_Asia	NA
155	VUT	548	Vanuatu	Southeast Asia	SE_Asia	NA
236	VEN	862	Venezuela	South America	S_Amer	Up_middle
237	VNM	704	Viet Nam	Southeast Asia	SE_Asia	NA
249	YEM	887	Yemen	Middle East	M_East	Low
251	ZMB	894	Zambia	Rest of Africa	RoAfr	NA
181	ZWE	716	Zimbabwe	Rest of Africa	RoAfr	NA
154		807	Macedonia, FYR	Eastern Europe	E_Euro	NA
80		70	Bosnia and Herzegovina	Eastern Europe	E_Euro	Low_middle
98		191	Croatia	Eastern Europe	E_Euro	Up_middle
198		705	Slovenia	Eastern Europe	E_Euro	Low_higher
255		56	Belgium	European Union+	EU	Up_higher
256		442	Luxembourg	European Union+	EU	Up_higher
167		203	Czech Republic	European Union+	EU	Up_middle
199		703	Slovakia	European Union+	EU	Up_middle

Appendix I. Selected Food Security Statistics

Commodities / Regions	A. Prices (100=2006)		B. Per capita consumption (100=2006)		C. Caloric content (kcal/grams)		D. Demand Elasticities				E. Standard deviation of caloric consumption
	2050		2050		2006	2050	Price		Income		
	Baseline	Demand only	Baseline	Demand only			2006	2050	2006	2050	
Crops											
World	92	169	109	99	-	-	-	-	-	-	-
Sub Saharan Africa			135	116	1.7	1.4	-0.31	-0.20	0.25	0.09	0.23
Central Asia			132	116	1.6	1.2	-0.30	-0.16	0.23	0.02	0.31
China/Mongolia			101	94	1.3	0.9	-0.23	-0.06	0.13	-0.12	0.31
Southeast Asia			113	101	2.1	1.7	-0.24	-0.14	0.15	-0.01	0.28
South Asia			130	115	2.1	1.6	-0.29	-0.15	0.22	0.01	0.28
Central America			97	90	1.6	1.4	-0.15	-0.08	0.01	-0.09	0.33
South America			99	92	1.5	1.3	-0.17	-0.10	0.04	-0.07	0.29
Livestock											
World	-	-	176	135	-	-	-	-	-	-	
Sub Saharan Africa	83	102	214	195	0.7	0.9	-0.50	-0.42	0.49	0.34	0.23
Central Asia	65	120	263	202	0.8	1.1	-0.49	-0.39	0.46	0.28	0.31
China/Mongolia	38	108	275	187	2.1	2.8	-0.44	-0.31	0.37	0.15	0.31
Southeast Asia	36	102	252	165	1.5	1.8	-0.45	-0.37	0.39	0.25	0.28
South Asia	49	108	294	210	0.9	1.1	-0.49	-0.38	0.46	0.27	0.28
Central America	33	104	188	125	1.1	1.3	-0.38	-0.33	0.27	0.18	0.33
South America	32	102	201	131	1.2	1.4	-0.40	-0.34	0.30	0.20	0.29
Processed Foods											
World	-	-	183	143	-	-	-	-	-	-	-
Sub Saharan Africa	66	117	270	195	1.8	1.4	-0.65	-0.51	0.55	0.38	0.23
Central Asia	67	111	295	227	4.9	1.2	-0.63	-0.45	0.52	0.31	0.31
China/Mongolia	65	128	245	186	1.7	0.9	-0.54	-0.33	0.42	0.16	0.31
Southeast Asia	67	112	214	166	3.3	1.7	-0.56	-0.43	0.44	0.27	0.28
South Asia	66	125	294	212	4.7	1.6	-0.62	-0.44	0.52	0.30	0.28
Central America	67	111	151	124	2.9	1.4	-0.44	-0.36	0.30	0.19	0.33
South America	67	113	161	129	2.8	1.3	-0.47	-0.38	0.33	0.21	0.29

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Uris Lantz C. Baldos was born in Laguna, Philippines and spent most of his childhood underneath the greeneries in the town of Los Baños. After high school, he attended the University of the Philippines at Los Baños where he received a B.S. in Economics in 2005. Uris worked in the private sector until he got accepted and attended the M.S. graduate program in Agricultural Economics at Purdue University in 2007. He continued on for his doctorate degree and worked as a Graduate Research Assistant at the Center for Global Trade Analysis, which is at the heart of the Global Trade Analysis Project, a global network of economists and policy analysts.

His research interest include international trade, agriculture and the environment, land use and food security. He is a co-author of the SIMPLE model – a partial equilibrium model of global agriculture – which has been used in several studies on agricultural land use, food prices, food security and climate change mitigation. It has also been used in interdisciplinary courses at Purdue University and Stanford University. Following his successful dissertation defense in August 2014, he started working as a Post-Doctoral Research Associate at the Center for Global Trade Analysis.