SIMPLE: a Simplified International Model of agricultural Prices, Land use and the Environment

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Abstract

In this paper, we document the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE). SIMPLE is a partial equilibrium model which is designed to better understand the competing forces that influence the global farm and food system and how these drivers influence long run agricultural land use, production, prices, GHG emissions and food consumption. SIMPLE has been developed under the principle that a model should be no more complex than is absolutely necessary to understand the basic forces at work. Therefore, unlike other global models which are generally more complex and disaggregated, SIMPLE is parsimonious and tractable. Indeed, our historical validation over the period 1961-2006 confirms that SIMPLE can be used to simulate the long run changes in the global farm and food system given exogenous shocks in a few key drivers of world agriculture. Equally important is that we demonstrated how SIMPLE can be used to assess the relative contribution of each of the individual drivers to the endogenous changes in world agriculture via the numerical and the analytical decomposition tools. With these tools at hand, SIMPLE offers a more robust analysis of both historical and future long run changes in the global farm and food system.

Keywords: world agriculture, long run analysis, land use, environment, biofuels, food consumption, SIMPLE

JEL: Q11, Q15, Q16, Q54

I. Introduction

Since the 2007/2008 commodity crisis, there has been a convergence of interest in the global farm and food system and its contributions to feeding the world's population as well as to ensuring the environmental sustainability of the planet. This has underscored the vulnerability of the global food system to shocks from extreme weather events, energy and financial markets, as well as government interventions in the form of export bans and other measures designed to avoid domestic adjustment to global scarcity. We have learned that a "perfect storm" in which all these factors coincide can have a severe impact on the world's poor, as well as putting considerable pressure on the world's natural resource base (Hertel, 2011). As we look ahead to the middle of this century, will the world's land resources be up to the task of meeting the diverse demands being placed on it?

The number of people which the world must feed is expected to increase by another 2 billion by 2050. When coupled with significant nutritional improvements for the 2.1 billion people currently living on less than $2/day, this translates into a very substantial rise in the demand for agricultural production. Over the past century, global agriculture has managed to offer a growing population an improved diet, primarily by increasing productivity on existing cropland. Can this feat be repeated in the next forty years? There are recent signs of slowing yield growth for key staple crops and public opposition to genetically modified crops has slowed growth in the application of promising biotechnology developments to food production in some parts of the world. How will this footrace between food demand and supply shape up in the next forty years? What role can agricultural technology play in alleviating potential scarcity?

In this context, the growing use of biomass for energy generation has contributed to concerns about future food scarcity. Indeed, over a two year period from 2005/6 – 2007/8, ethanol production in the US accounted for roughly half of the increase in global cereals consumption. To compound matters, water, a key input into agricultural production, is becoming increasingly scarce in many parts of the world. Since irrigated agriculture accounts for 70% of all freshwater withdrawals worldwide and about 40% of world agricultural output, such water scarcity is likely to impinge on global food availability and cost.

In addition, agriculture and forestry are increasingly envisioned as key sectors for climate change mitigation policy – offering low cost, near term abatement of greenhouse gas emissions. Yet any serious attempt to curtail these agricultural emissions will involve changes in the way farming is conducted, as well as placing limits on the expansion of farming – particularly in the tropics, where most of the agricultural land conversion has come at the expense of forests. Limiting the conversion of forests to agricultural lands is also critical to preserving the planet's biodiversity. These factors will restrict the potential for agricultural expansion in the wake of growing global demands.

Finally, agriculture is likely to be the economic sector whose productivity is most sharply affected by climate change. This will shift the pattern of global comparative advantage in agriculture and may well reduce the productivity of farming in precisely those regions of the world where malnutrition is most prevalent, while increasing yield variability and the vulnerability of the world's poor.

In order to better understand these competing forces and how they are likely to influence long run agricultural land use, production, prices, GHG emissions and nutrition, we develop the Simplified International Model of agricultural Prices, Land use and the Environment (SIMPLE). Unlike other global models which are generally more complex and disaggregated, SIMPLE is parsimonious and tractable. It has been designed using the principle that a model should be no more complex than is absolutely necessary to understand the basic forces at work. The main purpose of this paper is to provide a complete documentation of SIMPLE. We start by reviewing the structure of SIMPLE and its theoretical foundations (Section 2).We then outline the methods used to create SIMPLE's database and parameters (Section 3). We discuss the model calibration procedures and outline the steps for the historical validation of SIMPLE over the period 1961 to 2006 (Section 4). Finally, we discuss the results of the historical validation and compare these with the observed changes to evaluate how well SIMPLE captures the long run changes in the farm and food system at the global and regional level (Section 5).

II. Model Structure

Conceptual Model: At the core of SIMPLE is the theoretical model developed by Hertel (2011). He proposed a simple 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 of agricultural lands. These include the encroachment of urban lands into croplands and growth in the demand for land in ecosystem services. Finally, changes in agricultural yields (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:

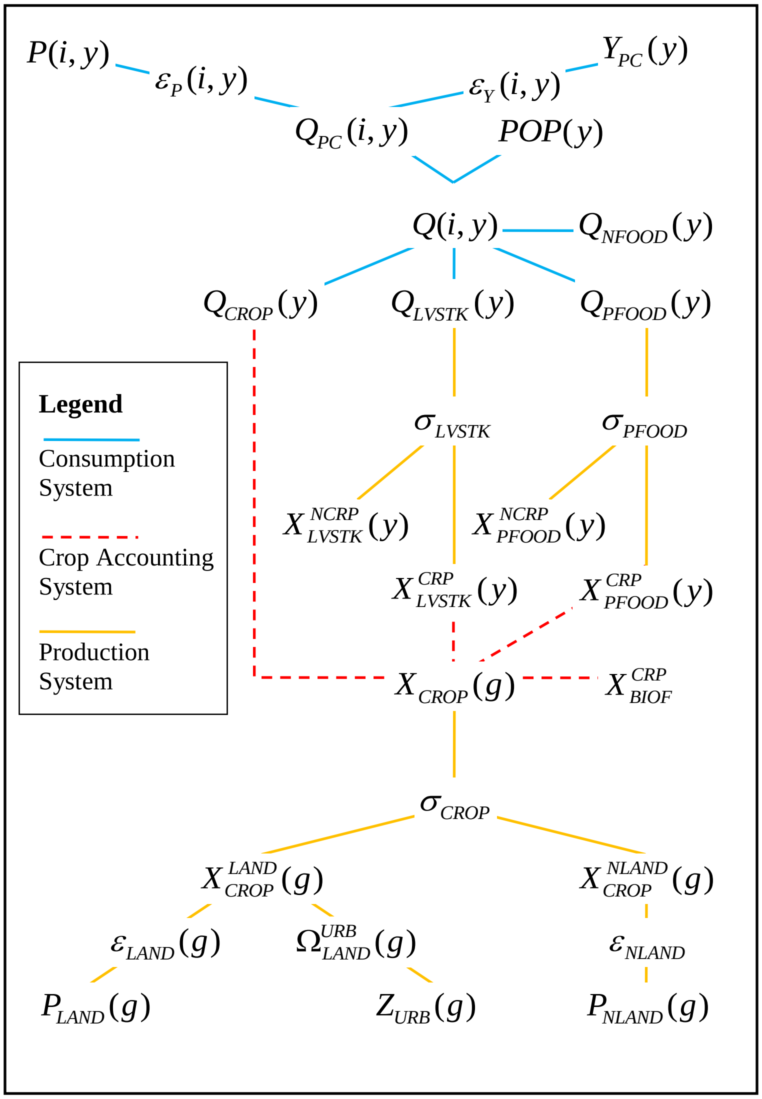
$$q_L^* = (\Delta_A^D + \Delta_L^S - \Delta_L^D) / (1 + \eta_A^{S,I} / \eta_A^{S,E} + \eta_A^D / \eta_A^{S,E}) - \Delta_L^S \tag{1}$$

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

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.

Empirical Model: In developing SIMPLE, we seek to retain the focus on these three margins of economic response, while introducing greater empirical detail by disaggregating the sources of demand and supply for agricultural products (Figure 1). In keeping with its name, the model is designed to be as simple as possible, while retaining sufficient geographic and sector richness to capture the global heterogeneity in the supply of, and demand for, global agricultural land. As with the model of Hertel (2011), there is a single, global market clearing condition for crop products. Crops are produced in *g* different geographic regions. Similarly the demand for agricultural output is derived from consumption in *y* different regional economies differentiated by per capita income level. These regional distinctions permit us to capture the differential impact of income growth on demand in different parts of the world, and similarly with questions of yield growth and land supply shifts across geographic regions. In the current version of the model, $g = 7$ and $y = 5$. However, these dimensions could be easily increased without a significant increase in the fundamental complexity of the model, as the crop market clears at global scale.

Figure 1. Structure of SIMPLE



Within each demand region, consumers demand four commodities, including both non-food $(NFOOD)$ and food products, differentiating between direct consumption of crops $(CROP)$, and indirect consumption through the demand for livestock products $(LVSTK)$ and processed food products $(PFOOD)$. The latter two categories are important since increases in the efficiency with which crops are used to produce these higher value products can have a significant impact on the global demand for cropland. Total consumption (Q) is equal to the product of population (POP) and per capita consumption (Q_{PC}). Key drivers of per capita consumption are commodity prices (P) and per capita incomes (Y_{PC}). The changes in these key drivers are then mediated by the price (ε_P) and income elasticities (ε_Y).

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. 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[1].

Total demand for crops in the model consists of the direct demand for crops (Q_{CROP}), demand for feedstocks in biofuel production (X_{BIOF}^{CRP}) as well as the derived demands for crops as feed for livestock (X_{LVSTK}^{CRP}), and as raw material inputs for processed food production (X_{PFOOD}^{CRP}). Production in the model uses the constant elasticity of substitution (CES) framework. Non-crop inputs are used in the production of livestock and processed food $(X_{LVSTK}^{NCRP}, X_{PFOOD}^{NCRP})$, and the parameters σ_{LVSTK} and σ_{PFOOD} govern the substitution between crop and non-crop inputs for

[1] Details regarding the demand elasticities are discussed in *Parameters* in Section 3

these sectors. In the case of livestock products, we expect that cheaper crop inputs may result in more intensive use of feedstuffs, per unit of livestock output.

In this framework, global supply is required to equal global demand for crops, with the equilibrating variable being the global price for crops (P_{CROP}). The global supply of crop outputs (X_{CROP}) is the summation of production across the geographic regions, each of which is characterized by differing land endowments and productivity. Two inputs are used during crop production, namely land (X_{CROP}^{LAND}) and non-land (X_{CROP}^{NLAND}) inputs. The parameter σ_{CROP} determines the substitution possibilities between these inputs. The larger this value, the greater the intensive margin of supply response. The supply of cropland, and hence the extensive margin of supply response, is a function of the returns to land in crop production in each region (P_{LAND}) as translated through the land supply elasticity (ε_{LAND}). Aside from its own-price supply response, we introduce a shifter in the cropland supply equation to represent the impact of urbanization on available croplands (Z_{URB}). We use a conversion factor (Ω_{LAND}^{URB}) to translate increases in urbanization to cropland loss. This is based on the ratio of urban lands to croplands and on the historical encroachment of urban lands in croplands.

The main departure from the model of Hertel (2011) is that we do not assume that the supply of non-land inputs is perfectly elastic. Instead, as with land, there is a finite elasticity of supply for these inputs (ε_{NLAND}) which means that the returns to these inputs (P_{NLAND}) are also endogenous. 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). It is also important to note that livestock and processed foods are assumed to be produced in the income region in which they are consumed. We do not model trade in these differentiated products so that prices for these composite food items can vary by region.

III. Database and Parameters

Database: To implement the model, we constructed a global database for the year 2001. A total of 119 countries were grouped by income into 5 demand regions. On the supply side, 7 geographic regions are identified. We rely on income groupings outlined in the World Development Indicators (2003) which is based on 2001 per capita gross national incomes[2]. This gives us a 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, crop production and urban land cover 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 data is taken from the GTAP V.6 database (2006) while data on cropland cover and production, utilization and prices of crops are derived from FAOSTAT (2011).We considered 50 crops including grains such as corn, rice, sorghum and oilseeds such as soybeans and rapeseeds. We define cropland in SIMPLE as arable land and permanent croplands and these total around 1.4 billion hectares worldwide. Finally, data on urban land cover was derived from Angel et al.(2010). Details regarding the crop and country coverage are listed in Appendices A and B, respectively.

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

We then combined the data above with additional information on industry cost and sales shares in order to construct the rest of the database. The value of crop production is around 612.5 billion USD globally. This is calculated from the crop price and quantity information from FAOSTAT. On the other hand, data on crop quantities require further processing. Note that we are aggregating quantities 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), we converted the crop quantities into corn-equivalent quantities using weights constructed from world crop prices and the world price of corn[3]. With this, the total quantity of crop production in the base data is around 5.8 billion metric tonnes of corn-equivalent production. We then allocate the normalized quantities across uses. We first separate the amount of crop feedstock used by the global biofuel sector using the sales shares by the global crop sector taken from GTAPBIO V.6 (Taheripour, Birur, Hertel, & Tyner, 2007). Shares constructed from the crop utilization data were 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).

We then calculated the global crop price, which amounts to around 106 USD per metric tonne of corn equivalent, from the value of crop production and the normalized quantity data. Using the global price and the allocated quantities, we then derived the value of crop input use in the livestock and processed food industries. Under the assumption of zero profits, we calculated the total value of land and non-land input costs in the regional crop sectors using GTAP v.6 cost shares as our guide. We also used the GTAP data base as a guide in classifying each geographic

[3]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

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. We again used GTAP v.6 cost shares and the value of crop input usage in the livestock and process food industries to impute the value of non-crop inputs used in these sectors. Finally, land rents and crop yields for each geographic region were derived using the value of land inputs, crop production and cropland areas. Table 1 shows the global values of key variables in SIMPLE in the base year. Details regarding the model's database and cost share assumptions are reported in Appendix C.

Table 1. Global values of selected variables in SIMPLE for base year 2001

Crop Production Data	
Crop Output (in M Mt)	5,778
as Biofuel Feedstock	43
as Livestock Feed	1,026
as Processed Food Inputs	2,248
as Food	2,460
Value of Crop Production (in B USD)	612
Crop Price (in USD per Mt)	106
Cropland Area (in M ha.)	1,400
Other variables	
Population (in M)	5,591
Income (in B USD)	31,195
Built-up/Urban land area (in M ha.)	58

Parameters: Parameters which guide consumption and production behavior in SIMPLE were 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 were 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).We used estimates of the unconditional Frisch own-price and expenditure elasticities for food subcategories. We then link the elasticities with per capita income growth using the estimates from linear regressions of these estimated demand elasticities on per capita incomes, as reported in the Appendix D. Values of the adjusted demand elasticities for year 2001 are listed in Table 2[4].

Table 2. Values of the adjusted demand elasticities in SIMPLE for year 2001

Regions	Crops	Livestock	Processed Foods	Non-food
Income Elasticities				
Upper high	-0.14	0.13	0.14	1.01
Lower high	-0.09	0.18	0.19	1.04
Upper middle	0.04	0.29	0.32	1.1
Lower middle	0.16	0.4	0.45	1.17
Low	0.27	0.5	0.56	1.23
Price Elasticities				
Upper high	-0.05	-0.30	-0.32	-0.74
Lower high	-0.08	-0.33	-0.36	-0.76
Upper middle	-0.17	-0.39	-0.46	-0.81
Lower middle	-0.25	-0.46	-0.57	-0.86
Low	-0.32	-0.51	-0.66	-0.90

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, while the income elasticity of demand for the non-food commodity is greater than one in all regions, so that the budget share of food will fall with rising incomes. We considered including the cross-price elasticities of demand between crops,

[4] The methods used to adjust these demand elasticities are discussed in Section 4

livestock and processed food, as well. However, the Florida Demand System did not offer a globally regular method for computing these elasticities. As an alternative, we have developed a version of the model using the AIDADS complete demand system as estimated by Cranfield, Preckel, Eales and Hertel (2002). This has attractive Engel curves, but it has overly simplistic own-price elasticities of demand, and these are critical for our analysis. Therefore, the results reported below are from our *ad hoc* demand model in which only own-price and income elasticities of demand are included. As we will see, this demand system performs well in our historical validation exercise. Of course the omission of cross-price effects would be more problematic if we were to use a more disaggregated set of commodities.

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 were taken from Ahmed, Hertel and Lubowski (2008). We also used the regional elasticities of land supply from Gurgel, Reilly and Paltsev (2007). These were 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 US elasticities were 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. We also scale-up the global supply elasticity of non-land inputs for long run experiments using the ratio of the 5-year and 15-year land supply elasticity as a guide.

Table 3 lists the 5-year and 15-year supply elasticities for land and non-land inputs. The land supply elasticities reflect the relative scarcity of new croplands across geographic regions. From the table, we see that regions wherein additional croplands are relatively abundant include

Table 3. 5-year and 15-year land and non-land supply elasticities in SIMPLE

Supply Elasticities	5-year	15-year
Land		
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
Non-land		
All regions	0.49	1.34

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.

Another important parameter is the factor used for converting urban expansion into cropland loss. We computed this factor for each geographic region. To derive this, we first calculated the ratio of urban lands to croplands using land cover information from SIMPLE's database. We then combined this ratio with the proportion of urban lands coming out of croplands. The literature on historical cropland loss due to urbanization is limited; hence, we apply some of the calculated proportions for multiple geographic regions. For example, in the U.S. around 22.9% of newly developed lands during 2002-07 were from croplands (U.S. Department of Agriculture, 2009). We use this figure for North America, Europe & Central Asia and Latin America & Caribbean regions. In China, roughly 46.3% of new urban lands came from croplands during 1980-2005 (Liu &Tian, 2010).This figure is applied to the East Asia & Pacific and South Asia regions. Finally, for Sub-Saharan Africa and Middle East & North Africa regions, we use the proportion of urban lands coming out of croplands in selected areas in Tunis during 1986 to 1996 which is around 39.3% (Weber & Puissant, 2003). Details of these parameters are listed in Appendix D.

IV. Model Calibration and Historical Validation

Model Calibration: We calibrate SIMPLE for the period 2001 to 2006 (5-years). This process allows us to adjust existing parameters, or generate unobserved parameters, by forcing certain variables in the calibration run to match the actual changes. Aside from this, model calibration is also important for updating the base data to 2006, which is in turn used as the base data for the long run experiments. There are four main steps in model calibration. First, using the price-yield response from Keeney and Hertel (2009) as a guide we ensure that a 1% increase in global crop price translates to a 0.25% increase in crop yields. This is done by adjusting the value of the global elasticity of substitution in crop production (i.e. change the starting value derived from Keeney and Hertel(2005)).

Second, due to the lack of independent estimates, we also calibrated the global elasticities of substitution between crop and non-crop inputs for the livestock sector by taking the change in feed use in livestock production of the upper high income region as our guide. This is done given exogenous shocks in population, income, biofuel use, urbanization and total factor productivity growth (TFP) in the crop, livestock and processed food sectors. Most of the historical growth rates were calculated from the sources used in the construction of the model's database with the exception of biofuel use and TFP growth. Biofuel growth rates were calculated using the historical estimates of energy demand from biofuels by the global transportation sector from the World Energy Outlook (International Energy Agency, 2006, 2007). Regional TFP growth rates for the crop, livestock and processed food sectors were derived from Fuglie (2010), Ludena et al

(2007) and from Emvalomatis, Stefanou and Lansink (2009), respectively. In SIMPLE, TFP is treated as an endogenous variable. To make TFP exogenous, we swapped these variables with the rate of non-crop, input-biased technological change for the livestock and processed food sectors while for the crop sector we swap TFP with the rate of Hick-neutral technological change. By swapping TFP with these variables, we can ensure that the rate of technological change in the model is precisely sufficient to hit the measured TFP growth rates in each region/sector.

In our initial calibration effort, we observed that the simulated change in global crop demand for food (10.9%) is nearly one-quarter greater than the historical change (around 8.8%). Since SIMPLE is designed for long run projections, it important that we closely capture the 5-year changes in crop demand for food consumption. Given this, for our third step we calibrated estimates of the demand elasticities 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). This dampens the magnitude of the regression intercepts while maintaining the values of the regression slopes (see Table 2). With these adjusted demand elasticities, the simulated change in global crop demand for food (8.4%) is now closer to the historical changes.

Lastly, we calibrated the elasticity of substitution for the livestock sector (around 0.62) given the exogenous shocks. We set the elasticity of substitution between crop inputs and non-crop inputs for the processed food sectors to zero under the assumption that this relationship is fixed over time. Finally, we kept the cost share of land inputs in the crop sector constant over this period so these cost shares are the same between the original (2001) and updated (2006) databases.

Historical Validation: After model calibration, we seek to validate SIMPLE, by undertaking projections over a longer time period – akin to the kind of long run projections for which we anticipate using the model. Accordingly, we simulate it over the 45-year period from 1961 to 2006[5]. For this validation exercise, we use the long run land and non-land supply elasticities. We shock a set of exogenous variables which includes: population and per capita incomes by demand region, and TFP growth rates by geographic region for the crop sector, and by income region for the livestock and the processed food sectors. These growth rates were taken from the same sources used in computing the shocks needed for model calibration[6]. To target TFP growth rates, we employ the same strategy as mentioned above.

We implement SIMPLE using the GEMPACK program (Pearson, Hertel, & Horridge, 2000) which has many useful features for purposes of analysis. One of these is the subtotals feature developed by Harrison, Horridge and Pearson (2000) which utilizes numerical integration techniques in order to exactly partition the impacts of different exogenous shocks on endogenous variables of interest. In addition, we also used the AnalyzeGE program (Pearson, Hertel & Horridge, 2000) to help decompose key equilibrium equations on changes in global crop demand, crop yield and croplands as well as provide analytical explanations regarding these changes in relation to the exogenous drivers and endogenous changes in prices. Details regarding the value of the exogenous shocks used in the model calibration and historical validation are outlined in Appendix E.

[5] The historical validation from 1961 to 2006 requires a 1961 base data. We generate this base data via a "backward" validation (i.e. 2006 to 1961) experiment using the 2006 base data generated during the model calibration process. Key results of the model calibration and "backward" validation are indicated in Appendix F.

[6] Due to the limited data, the country coverage for the historical validation is only for 101 countries (compared to 119 countries). Given this, all the exogenous shocks and the actual changes are calculated from this subset of countries.

V. Results and Discussion

Global results: Validating SIMPLE over this long run historical period allows us to assess how well the model simulates the long run changes in the global agricultural system given only exogenous growths in population, incomes and TFP. Figure 2 summarizes the simulated and observed changes for selected global variables. We see that the predicted change in global crop output (259.5%) is relatively larger than the observed change during 1961 to 2006 (214.6%). On the other hand, the predicted global cropland use and crop price (16.5% and -34.0%, respectively) are quite close to the historical changes (16.2% and -36.3%[7], respectively). Given the changes in crop output and cropland, we can deduce that the simulated changes in crop yields are greater than the actual changes (242.2% and 198.4%), respectively. Obviously, there are other exogenous factors which influence the changes in global crop variables during this period. We are also abstracting from the cross-price effects across consumer goods given the *ad hoc* demand system in the model. Nonetheless, we deem this to be a reasonable approximation to observed values over this extended period of 45 years and conclude that SIMPLE can be used to simulate long run cropland use and price changes at the global scale.

One of the main advantages offered by SIMPLE is the capacity to quantify the respective contributions of the key drivers to the changes in global crop land use and price as well as other endogenous variables. This can be clearly seen in the results of the historical validation. In Table 4, we numerically decompose the impacts of exogenous changes in population, income and technological changes to a selection of global endogenous variables. Looking at the decomposed

[7] This is based on the world price index of food grains (in real 2005$: 2005=100) from the Global Economic Monitor Commodities database by the World Bank

Figure 2. Simulated and actual changes in key global variables: 1961-2006

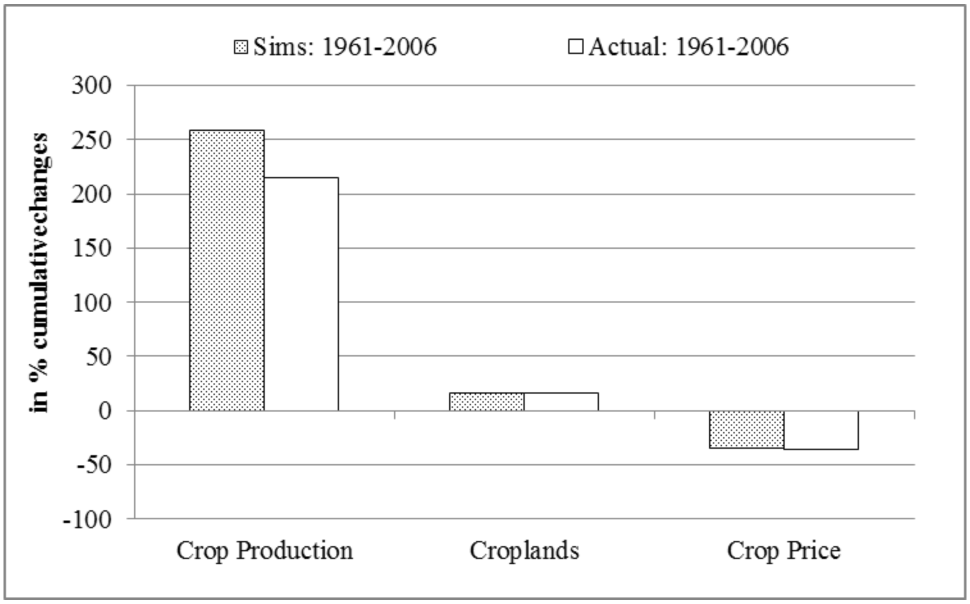

Table 4. Subtotals of key drivers of the global farm and food system (in cumulative %)

Variable	Total Effect	Subtotals of Individual Drivers				
		Per Capita Income	Population	Technical Change		
				Crop	Livestock	Processed Food
Agricultural Variables						
Crop Price	-34.0	23.4	46.5	-117.3	14.4	-1.0
Crop Output	259.5	49.6	112.3	66.5	33.6	-2.5
Cropland	16.5	12.5	26.0	-29.4	7.9	-0.6
Crop Yield	208.5	25.2	56.1	111.7	16.8	-1.2
Crop demand						
Food	187.5	25.4	108.0	61.0	-7.5	0.6
Feedstuff	220.3	44.0	45.3	166.2	-20.4	-14.8
Crops	519.2	122.0	204.2	11.7	181.2	0.1
Food demand						
Livestock	129.7	39.3	68.7	4.3	-0.5	18.0
Processed Food	361.3	80.4	139.3	7.3	134.3	0.1

impacts, we see that population growth makes a larger contribution to the global crop system, relative to income. The average factor of proportionality is roughly 2.1 for all global crop variables, meaning that population was a far more important demand driver of the global farm and food system than income during this historical period. However, the main driver of global crop price and cropland use is TFP growth in the crop sector. Its impact is large enough to offset the upward pressures in global crop price due to population and income growth combined.

A closer look at food consumption shows that the simulated demand increase is largest for processed foods, followed by the demand for crop and livestock commodities (361.3%, 187.5% and 129.7%, respectively). The numerical decomposition of these changes suggests that population rather than income growth has made a larger contribution to the global growth in food consumption. Globally, the factor of proportionality between income and population for food crops, livestock and processed foods are roughly 4.3, 1.7 and 1.7, respectively.

Regional results: As mentioned earlier, the figures generated from SIMPLE closely follow the actual changes during this historical period, in particular, the global changes in agricultural land use and price. To check if SIMPLE can reproduce the observed changes at the regional level, we look at the simulated changes for crop production and cropland use. We report the regional figures for crop production in Table 5. Focusing on percent changes, we see that the simulated change is close to the actual change only in South Asia. The simulated changes are lower than the actual changes for Middle East & North Africa and Sub-Saharan Africa while it is higher for the remaining regions. Contrary to what we observed in the global results, the regional decomposition suggests that population growth is not always the main driver of crop production. For East Asia & Pacific and South Asia, crop TFP growth is the main driver of crop production with factor proportionality with respect to population at around 1.5 and 1.4, respectively.

Table 5. Comparison of crop production across geographic regions (values in cumulative %)

Geographic Regions	Crop Production		Subtotals of Individual Drivers				
	Actual Change	Historical Validation	Per Capita Income	Population	TFP: Crop	TFP: Livestock	TFP: Processed Food
East Asia & Pacific	309.1	547.7	73.1	171.0	256.6	50.8	-3.8
Europe & Central Asia	131.7	190.8	35.5	79.1	54.2	23.8	-1.7
Latin America & Caribbean	271.5	573.5	99.2	234.8	175.3	69.5	-5.3
Middle East & North Africa	286.5	195.7	47.9	107.1	10.9	32.1	-2.4
North America	148.3	237.3	39.2	88.1	85.5	26.4	-2.0
South Asia	226.4	232.5	51.2	115.6	33.6	34.6	-2.6
Sub-Saharan Africa	274.3	24.5	36.8	77.1	-111.2	23.5	-1.7
TOTAL	**214.6**	**259.5**	**49.6**	**112.3**	**66.5**	**33.6**	**-2.5**

Looking at cropland use (Table 6), we see again that the simulated increases are greater than actual expansion in many regions. However, there are also regions wherein the direction of the simulated changes differs from the actual changes. In Europe & Central Asia and North America, the simulated changes are positive (8.4% and 10.4%, respectively) while actual data shows that cropland use contracted in these regions (-13.3% and -8.5%, respectively). This likely reflects institutional changes associated with the transition of Central and Eastern European countries from centrally planned economies to more liberal economic regimes. This type of institutional consideration is something that is not presently captured in SIMPLE. It would most logically be treated as a shift in the cropland supply schedule.

For Sub-Saharan Africa, cropland use actually expanded while the model suggests that it should have contracted (52.1% and -7.5%, respectively) due to the estimated decline in total factor productivity over this period. TFP growth in the crop sector is generally the main driver of regional cropland use. This is because we assume perfectly integrated markets. However, over much of this period, agricultural markets were been highly segmented, with high tariffs and non-tariff barriers preventing competitive regions from exporting to less-competitive regions. Since completion of the Uruguay Round of GATT/WTO negotiations, many of these border measures

Table 6. Comparison of crop production across geographic regions (values in cumulative %)

Geographic Regions	Cropland Use		Subtotals of Individual Drivers				
	Actual Change	Historical Validation	Per Capita Income	Population	TFP: Crop	TFP: Livestock	TFP: Processed Food
East Asia & Pacific	34.8	20.3	7.5	15.6	-7.2	4.8	-0.3
Europe & Central Asia	-13.3	8.4	6.3	12.9	-14.5	4.0	-0.3
Latin America & Caribbean	63.1	81.3	33.6	72.6	-45.3	21.9	-1.6
Middle East & North Africa	27.2	19.7	16.4	34.1	-40.4	10.4	-0.7
North America	-8.5	10.4	6.4	13.1	-12.8	4.0	-0.3
South Asia	7.8	23.0	16.2	33.9	-36.7	10.3	-0.7
Sub-Saharan Africa	52.1	-7.5	23.6	48.3	-93.2	14.8	-1.0
TOTAL	**16.2**	**16.5**	**12.5**	**26.0**	**-29.4**	**7.9**	**-0.6**

have been limited, and markets for agricultural products have become more integrated. This change in the degree to which regions trade in food products will likely continue to evolve over the coming decades. It clearly plays a large role in shaping the regional pattern of global food production.

Contrary to the results at the global level, these results highlight the limitations of SIMPLE in capturing regional historical changes in crop production and cropland use. With the current set of calibrated parameters and shocks, caution should be exercised when looking at the simulated changes from SIMPLE at the regional level.

We can take a closer look at changes in global food demand by decomposing the relative contribution of population and income growth in each income region to global food demands. Table 7 reports such a decomposition, wherein the impact of regional growth in population and income on global food demand is disaggregated. The final row reports the combined impact of population and income growth in all regions, which corresponds to the global figures reported in Table 4. Note from the first pair of columns in Table 7 (food crops), that most of the growth in direct demand for crops arises in the lower income regions – primarily the low middle and low income regions. For these regions, the impacts of both population and income growth are mainly

Table 7. Regional subtotals of population and income on food demands (values in cumulative %)

Income Regions	Food Demand					
	Food Crops		Livestock		Processed Food	
	Population	Per Capita Income	Population	Per Capita Income	Population	Per Capita Income
Upper high	11.1	-5.6	44.8	24.8	50.0	28.4
Lower high	0.2	0.0	0.3	0.1	0.3	0.1
Upper middle	5.4	-0.5	9.7	2.5	34.3	9.8
Lower middle	49.5	19.5	11.9	10.8	24.1	23.4
Low	41.8	12.0	2.0	1.1	30.5	18.7
TOTAL	**108.0**	**25.4**	**68.7**	**39.3**	**139.3**	**80.4**

positive with the former having a larger magnitude relative to the latter. For livestock, bulk of the increase in global consumption is mainly due to population and income growth in the upper high income region. The impacts of these drivers in this region are 44.8% and 24.8%, respectively, which are more than 60% of the contribution of world population and income growth to the global livestock consumption. Finally, population growth in all regions – except in the lower high income region – contributes significantly to the global demand in processed foods. With respect to income, regions which contribute greatly to processed food consumption are the upper high and the lower middle income regions (28.4% and 23.4%, respectively).

Analytical Decomposition: In addition to these numerical decompositions, we can also employ analytical decompositions to gain further insight into the changes in global crop demand and crop yield during this historical period. Unlike the numerical decomposition (i.e. subtotals), the analytical decomposition is based on the structure of the underlying economic model. In particular, we can substitute selected behavioral equations in SIMPLE[8] into the expressions for global crop demand and crop yield as follows:

[8] The analytical decomposition of global crop demand (Eq 3.a and 3.b) is derived from the equations on global market clearing for crops, food demand for crops and derived demands for crop input in the livestock and processed food sectors. For global crop yield (Eq 4.), we use the equations on derived demand and supply for croplands.

$$\hat{Q}_{CROP} = \theta_{BIOF}\hat{X}_{BIOF} + \theta_{NBIOF}\sum\phi_{(y)}\hat{X}_{NBIOF(y)} \tag{3.a}$$

$$\hat{X}_{NBIOF(y)} = P\hat{O}P_{(y)} + \sum\Omega_{(i,y)}\left(\varepsilon^{Y}_{(i,y)}Y\hat{P}C_{(y)} + \varepsilon^{P}_{(i,y)}\hat{P}_{(i,y)}\right)$$

$$+\Omega_{(LVSTK,y)}\sigma_{LVSTK}(\hat{P}_{(LVSTK,y)} - \hat{P}_{CROP}) \tag{3.b}$$

$$Y\hat{L}D = \sum\left(\varphi_{(g)} - \tau_{(g)}\right)\varepsilon^{LAND}_{(g)}\hat{P}^{LAND}_{(g)} + \varphi_{(g)}(1-\sigma_{CROP})\hat{\alpha}_{(g)}$$

$$+\varphi_{(g)}\sigma_{CROP}(\hat{P}^{LAND}_{(g)} - \hat{P}_{CROP}) \tag{4}$$

At the global level (Eq.3a) shows that changes in crop demand are dictated by a weighted combination of global biofuel and regional food demands ($\hat{X}_{BIOF}, \hat{X}_{NBIOF(y)}$), where the weights are given by their respective crop consumption shares ($\theta_{BIOF}, \theta_{NBIOF}$). Since there are no biofuel shocks implemented in the historical period, global crop demand is solely driven by regional demands which are weighted by the crop consumption shares in each income region ($\phi_{(y)}$).

Regional crop demands are comprised of 4 components, namely population, income, food price and input substitution effects (Eq.3.b). Population growth directly contributes to regional crop demand ($P\hat{O}P_{(y)}$). Changes in per capita income and endogenous food prices ($Y\hat{P}C_{(y)}, \hat{P}_{(i,y)}$) are initially translated to changes in food consumption via the food income and price elasticities ($\varepsilon^{Y}_{(i,y)}, \varepsilon^{P}_{(i,y)}$), respectively. These are then further converted to crop-equivalent using the crop consumption shares ($\Omega_{(i,y)}$) in each food sector. Adjustments in crop input use due to price changes are captured via the input substitution effect. Recall that we assumed that the processed food sector uses inputs in fixed proportions so this effect is only present in the livestock sector. Input substitution is driven by changes in and the price of crops, relative to non-crop inputs, or alternatively, output price (which is itself a combination of crop and non-crop input prices. If global crop price rises faster (slower) than livestock prices – a situation which arises if non-crop prices rise more slowly – then this sector uses feed inputs less intensively. Changes in relative output and input prices are further weighted by the crop consumption share and the elasticity of substitution in the livestock sector.

Similarly, global crop yield ($\hat{YLD}$) is dictated by changes in yields at the regional level (Eq.4). Crop yields in each geographic region have 3 components: productivity of new croplands, TFP growth, and the input substitution effect. Additional croplands are determined by the land supply elasticities and land rents ($\varepsilon_{(g)}^{LAND}, \hat{P}_{(g)}^{LAND}$). However, the average productivity of the new lands is determined by the regional crop production and cropland shares ($\varphi_{(g)}, \tau_{(g)}$). If the crop production share is larger (smaller) than that of cropland then new lands in that region have high (low) yields, relative to the global average. The impact of TFP growth ($\hat{\alpha}_{(g)}$) is weighted by the crop production share and the elasticity of substitution in the crop sector (σ_{CROP}). If land and non-land inputs are close substitutes (complements) then the impact of TFP growth on crop yields is decreased (increased). With the input substitution effect, there is an incentive to substitute away from land to non-land inputs if land rents rise faster than non-land input prices, or equivalently if land price rise relative to crop output prices ($\hat{P}_{(g)}^{LAND} > \hat{P}_{CROP}$). In turn, this increases crop yields since more non-land inputs are used. This effect also depends on the crop production shares and the elasticity of substitution in the crop sector.

The results of the analytical decomposition of global crop demand and crop yield are summarized in Tables 8 and 9. In Table 8, we see that the crop consumption share is highest in the upper high income region (46.5%) followed by the lower middle and low income regions (27.1% and 16%, respectively). This implies that a percent change in crop demand in the upper high income region has a larger effect on global crop demand than in other regions. This is also the reason why crop demand changes in the lower high income region contribute little to global crop demand. Among the components of regional crop demands, population growth has the largest impact followed by income growth and food prices (73.4%, 33.5% and 29.7%, over this historical period. Across income regions, demand changes in the lower middle and the low income regions are the main contributors to global crop demand (55.7% and 37.9%, respectively). During this historical period, population grew faster in the low than in the lower middle income region. However, the impact of population growth in the latter region is further magnified by its crop consumption share. Aside from the population driver, income growth in the low middle and low income regions are also notable. The impact of rising incomes on crop demand in these regions is further magnified by their food income elasticities which are higher than in other regions due to the implications of dietary upgrading (See Table 2). Endogenous food prices during this historical period are falling for all regions and this increases food demand. For the low middle and low income regions, the impact of falling food prices on food demand is further amplified by their food price elasticities.

Table 8. Analytical decomposition of global crop demand[9]

Crop Demand	Crop Allocation Share	Population	Per Capita Income	Food Price	Input Substitution	**TOTAL**
Upper high	46.5	12.0	3.5	6.8	1.1	**23.4**
Lower high	0.1	0.1	0.0	0.0	0.0	**0.2**
Upper middle	10.4	11.3	2.4	5.4	-0.2	**19.0**
Lower middle	27.1	28.0	19.0	10.1	-1.4	**55.7**
Low	16.0	21.9	8.5	7.3	0.1	**37.9**
TOTAL	**100**	**73.4**	**33.5**	**29.7**	**-0.4**	**136.1**

[9] Note that changes in global crop demand and crop yield (lower right hand corner values in Tables 8 and 9) are different in the analytical decomposition and figures in Table 4. This occurs because we are applying solutions derived from non-linear methods to linear expressions. There are non-linear interactions among the key equations of SIMPLE so we use non-linear methods to solve the model. Contrary to this, our analytical decompositions are essentially linear expressions of the equilibrium changes in global crop demand and crop yield.

Table 9. Analytical decomposition of global crop yield

Crop Yields	Crop Production Share	Cropland Share	Productivity of New Lands	TFP Growth	Input Substitution	**TOTAL**
East Asia & Pacific	16.8	18.3	0.9	13.4	32.0	**46.4**
Europe & Central Asia	26.5	26.8	-0.2	8.7	16.4	**25.0**
Latin America & Caribbean	6.5	7.2	0.1	4.7	8.1	**12.8**
Middle East & North Africa	4.2	3.4	0.1	1.3	2.2	**3.5**
North America	13.2	17.3	-0.4	5.1	9.9	**14.6**
South Asia	15.6	13.9	0.2	5.6	10.0	**15.8**
Sub-Saharan Africa	17.3	13.1	0.1	1.5	1.5	**3.0**
TOTAL	**100**	**100**	**0.8**	**40.2**	**80.1**	**121.0**

Looking at the results, we see that input substitution and TFP growth are the main contributors to global crop yield (80.1% and 40.2%, respectively). Among geographic regions, most of the growth in global yield comes from the East Asia & Pacific and Europe & Central Asia regions (46.4% and 25.0%, respectively). Yield changes in the East Asia & Pacific region are largely due to strong growths in TFP and in endogenous land rents while for the Europe & Central Asia region changes in TFP and land rents are modest but these are magnified by the region's crop production share (26.5%). Overall impact of productivity of additional lands on global crop yield is negligible for this historical period.

Exogenous shocks in population and income directly affect global crop demand while TFP growth directly affects global crop yields. However, these shocks also have indirect effects on other components of global crop demand (food price, input substitution) and crop yield (productivity of new lands, input substitution). By integrating the numerical with the analytical decomposition, we can explore the subtotals of the analytical components of the global crop demand and crop yield. The combined decomposition is reported in Table 10. Focusing on crop demand, the direct effects of population is larger than that of income growth (73.4% and 33.5%, respectively). Note that, these are the same figures in Table 8. However, with the combined decomposition we can see that population and income growth also reduces crop demand via higher food prices (-7.4% and -3.7%, respectively) and via input substitution (-5.8% and -2.9%, respectively) due to higher feed prices. On the other hand, the exogenous TFP growths in the crop, processed food and livestock sectors indirectly affect crop demand by dampening food prices which in turn encourages food consumption (40.8%) and use of more feed inputs (8.3%). Looking at crop yields, we see that only the technical change in the crop sector has a direct effect of increasing yields. However, most of the exogenous drivers have indirect effects on crop yields via input substitution in the crop sector.

Table 10. Combined decomposition of global crop demand and crop yield

Components of Global Cropland Demand	Population	Per Capita Income	TFP Growth
Crop Demand			
Direct Effect	73.4	33.5	-
Indirect Effect			
via Food Prices	-7.4	-3.7	40.8
via Input Substitution			
in Livestock Sector	-5.8	-2.9	8.3
Net Effect	**60.1**	**26.9**	**49.1**
Crop Yields			
Direct Effect	0	0	40.2
Indirect Effect			
via Productivity of New Lands	-0.2	0	0.9
via Input Substitution	32.6	15.6	31.8
Net Effect	**32.4**	**15.7**	**72.9**

IV. Summary and Conclusion

In this paper, we provide complete documentation of the SIMPLE model. We outline the theoretical and structural framework of the model. We also highlight the key differences between our empirical framework and the theoretical framework by Hertel (2011) upon which this is based. To implement the model, we constructed a global base data for year 2001 given key data on cropland use, agricultural and socio-economic variables taken from several sources. We also used cost and sales shares from selected GTAP databases in order to complete our base data. We then outlined the procedures in calibrating the model over the 2001 to 2006 period. During model calibration, we adjusted existing or generated missing model parameters as well as updated the base data from 2001 to 2006. Once calibrated, we used the updated 2006 base data to validate SIMPLE, by back-casting over the period 1961 to 2006 (45 years) given the historical growth in population, per capita incomes and total factor productivity.

The historical validation shows that the simulated global crop production is somewhat greater than the observed changes but the simulated changes for cropland use and price closely follow the observed changes. This is encouraging and it confirms that SIMPLE can be used to simulate the long run changes in the global farm and food system given exogenous shocks in the key drivers of world agriculture. Although a closer look at the regional changes in cropland and crop production suggests that caution must be exercised when interpreting the regional results from SIMPLE. In many regions, the simulated changes exceed the actual changes in cropland use and crop production. This is likely a consequence of our assumption about fully integrated global markets for crops, which is overly strong given the degree of government intervention in food trade over this period.

Equally important is that we demonstrated how SIMPLE can be used to assess the relative contribution of each of the individual drivers to the endogenous changes in global agriculture via the numerical and the analytical decomposition tools. Using the numerical decomposition, we observed that during this 45-year historical period, global crop demand was mainly driven by population and not income growth while global changes in crop price and cropland use were mainly driven by TFP growth in the crop sector. Given the analytical decomposition tool, we illustrated how global changes in crop demand and crop yield are driven by changes in the exogenous drivers and endogenous output and input prices. We also combined both analytical and numerical decomposition to explore the subtotals of the analytical components of the global crop demand and crop yield. With these decomposition tools at hand, SIMPLE offers a more robust analysis of the marginal impacts of the key drivers of both historical and future long run changes in the world agriculture.

References

Ahmed, S. A., Hertel, T., & Lubowski, R. (2008). *Calibration of a Land Cover Supply Function Using Transition Probabilities* (GTAP Research Memorandum No. 14). Retrieved from http://www.gtap.agecon.purdue.edu/resources/res_display.asp?RecordID=2947

Aiking, H., Zhu, X., van Ierland, E., Willemsen, F., Yin, X., & Vos, J. (2006). Changes in consumption patterns: options and impacts of a transition in protein foods. *Agriculture and climate beyond 2015* (pp. 171–189). The Netherlands: Springer.

Angel, S., Parent, J., Civco, D., Blei, A., & Potere, D. (2010). *A Planet of Cities: Urban Land Cover Estimates and Projections for All Countries, 2000-2050* (Working Paper). Cambridge, MA, USA: Lincoln Institute of Land Policy.

Cranfield, J. A., Preckel, P. V., Eales, J. S., & Hertel, T. W. (2002). Estimating consumer demands across the development spectrum: maximum likelihood estimates of an implicit direct additivity model. *Journal of Development Economics*, *68*(2), 289–307. doi:16/S0304-3878(02)00014-7

Dimaranan, B. V. (Ed.). (2006). *Global Trade, Assistance, and Production: The GTAP 6 Data Base*. West Lafayette, Indiana, USA: Center for Global Trade Analysis, Purdue University.

Emvalomatis, G., Stefanou, S. E., & Lansink, A. O. (2009). Dynamic Decomposition of Total Factor Productivity Change in the EU Food, Beverages, and Tobacco Industry: The Effect of R&D. *A resilient European food industry and food chain in a challenging world*. Presented at the 113th European Association of Agricultural Economists Seminar, Chania, Crete, Greece.

FAOSTAT. (2011, January 13). Retrieved January 13, 2011, from http://faostat.fao.org/

Foresight. (2011). *The Future of Food and Farming: Challenges and choices for global sustainability*. London, UK: The Government Office for Science.

Frazão, E., Meade, B., & Regmi, A. (2008, February). Converging Patterns in Global Food Consumption and Food Delivery Systems. *Amber Waves*, *6*(1). Retrieved from http://www.ers.usda.gov/AmberWaves/February08/

Fuglie, K. O. (2010). Total Factor Productivity in the Global Agricultural Economy: Evidence from FAO Data. *The Shifting Patterns of Agricultural Production and Productivity Worldwide* (pp. 63–93). Ames, Iowa: The Midwest Agribusiness Trade Research and Information Center, Iowa State University.

Gurgel, A., Reilly, J. M., & Paltsev, S. (2007). Potential Land Use Implications of a Global Biofuels Industry. *Journal of Agricultural & Food Industrial Organization*, Journal of Agricultural & Food Industrial Organization, *5*(2). Retrieved from http://ideas.repec.org/a/bpj/bjafio/v5y2007i2n9.html

Harrison, W. J., Horridge, J. M., & Pearson, K. R. (2000). Decomposing Simulation Results with Respect to Exogenous Shocks. *Computational Economics*, Computational Economics, *15*(3), 227–249.

Hayami, Y., & Ruttan, V. W. (1985). *Agricultural Development: An International Perspective*. Baltimore: Johns Hopkins University Press.

Hertel, T. (2011). The Global Supply and Demand for Land in 2050: A Perfect Storm? *American Journal of Agricultural Economics*, AAEA Presidential Address, *93*(1).

International Energy Agency. (2006). *World Energy Outlook*.

International Energy Agency. (2007). *World Energy Outlook*.

Keeney, R., & Hertel, T. W. (2005). *GTAP-AGR: A Framework for Assessing the Implications of Multilateral Changes in Agricultural Policies* (GTAP Technical Paper No. 24). Purdue University.

Keeney, R., & Hertel, T. W. (2009). The Indirect Land Use Impacts of United States Biofuel Policies: The Importance of Acreage, Yield, and Bilateral Trade Responses. *American Journal of Agricultural Economics*, *91*(4), 895–909.

Liu, M., & Tian, H. (2010). China's land cover and land use change from 1700 to 2005: Estimations from high-resolution satellite data and historical archives. *Global Biogeochemical Cycles*, *24*, 18 PP. doi:201010.1029/2009GB003687

Ludena, C. E., Hertel, T. W., Preckel, P. V., Foster, K., & Nin, A. (2007). Productivity growth and convergence in crop, ruminant, and nonruminant production: measurement and forecasts. *Agricultural Economics*, *37*(1), 1–17. doi:10.1111/j.1574-0862.2007.00218.x

Muhammad, A., Seale Jr., J. L., Meade, B., & Regmi, A. (2011). *International Evidence on Food Consumption Patterns: An Update Using 2005 International Comparison Program Data* (Technical Bulletin No. TB-1929) (p. 59). Washington, D.C., USA: Economic Research Service, U.S. Department of Agriculture. Retrieved from http://www.ers.usda.gov/Publications/TB1929/

Pearson, K., Hertel, T., & Horridge, M. (2000). AnalyseGE: Software Assisting Modellers in the Analysis of their Results. *Practical Aspects of GE Modelling*. Presented at the Third Annual Conference on Global Economic Analysis, Melborne, Australia.

Salhofer, K. (2000). *Elasticities of Substitution and Factor Supply Elasticities in European Agriculture: A Review of Past Studies* (Discussion Paper No. 83-W-2000). Vienna, Austria: Department of Economics, Politics, and Law in the University of Agricultural Sciences Vienna.

Taheripour, F., Birur, D., Hertel, T., & Tyner, W. (2007). *Introducing Liquid Biofuels into the GTAP Data Base*. Center for Global Trade Analysis, Department of Agricultural Economics, Purdue University. Retrieved from https://www.gtap.agecon.purdue.edu/resources/download/3939.pdf

Tweeten, L., & Thompson, S. (2009). Long-term Global Agricultural Output Supply-Demand Balance and Real Farm and Food Prices. *Farm Policy Journal*, *6*(1).

U.S. Department of Agriculture. (2009). *Summary Report: 2007 National Resources Inventory* (p. 123). Washington, DC and Ames, Iowa: Natural Resources Conservation Service and Center for Survey Statistics and Methodology, Iowa State University. Retrieved from http://www.nrcs.usda.gov/technical/NRI/2007/2007_NRI_Summary.pdf

Weber, C., & Puissant, A. (2003). Urbanization pressure and modeling of urban growth: example of the Tunis Metropolitan Area. *Remote Sensing of Environment*, *86*(3), 341–352. doi:16/S0034-4257(03)00077-4

World Bank. (2003). *World Development Indicators - 2003*, *Volume 1* (No. 25830) (p. 422). Washington DC, USA. Retrieved from http://econ.worldbank.org/external/default/main?pagePK=64165259&theSitePK=469372&piPK=64165421&menuPK=64166093&entityID=000094946_03051504051563

World Bank. (2011). *World Development Indicators*. Washington DC, USA. Retrieved from http://data.worldbank.org/data-catalog/world-development-indicators

World Population Prospects: The 2010 Revision. (2011, August 23). Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat. Retrieved from http://esa.un.org/unpd/wpp/index.htm

Appendix A. List of crops in SIMPLE

Apples	Groundnuts, with shell	Plantains	Tea
Bananas	Lemons and limes	Potatoes	Tomatoes
Barley	Maize	Pulses, Other	Vegetables, Other
Beans, dry	Millet	Rapeseed	Wheat
Beans, green	Mustard seed	Rice, paddy	Yams
Cassava	Nuts	Roots, Other	
Cereals, nes	Oats	Rye	
Citrus fruit, nes	Olives	Sorghum	
Cloves	Onions (inc. shallots), green	Soybeans	
Cocoa beans	Onions, dry	Spices, Other	
Coconuts - Incl Copra	Oranges	Sugar beet	
Coffee, green	Peas, dry	Sugar cane	
Dates	Peas, green	Sunflowerseed	
Grapefruit	Pepper	Sweet potatoes	
Grapes	Pineapples	Tangerines, mandarins, clem.	

Appendix B. List of countries in SIMPLE

Country Name	Income Reg.	Geographic Region	Country Name	Income Reg.	Geographic Region
Albania	Low Middle	Europe & Central Asia	Kenya	Low	Sub-Saharan Africa
Algeria	Low Middle	Middle East & North Africa	Kyrgyzstan	Low	Europe & Central Asia
Argentina	Up Middle	Latin America & Caribbean	Lao People's Democratic Rep.	Low	East Asia & Pacific
Armenia	Low	Europe & Central Asia	Latvia	Up Middle	Europe & Central Asia
Australia	Up Higher	East Asia & Pacific	Lebanon	Up Middle	Middle East & North Africa
Austria	Up Higher	Europe & Central Asia	Lithuania	Up Middle	Europe & Central Asia
Azerbaijan	Low	Europe & Central Asia	Luxembourg	Up Higher	Europe & Central Asia
Bangladesh	Low	South Asia	Madagascar	Low	Sub-Saharan Africa
Barbados	Up Middle	Latin America & Caribbean	Malawi	Low	Sub-Saharan Africa
Belarus	Low Middle	Europe & Central Asia	Malaysia	Up Middle	East Asia & Pacific
Belgium	Up Higher	Europe & Central Asia	Maldives	Low Middle	South Asia
Belize	Low Middle	Latin America & Caribbean	Mali	Low	Sub-Saharan Africa
Bolivia	Low Middle	Latin America & Caribbean	Malta	Up Middle	Middle East & North Africa
Bosnia & Herzegovina	Low Middle	Europe & Central Asia	Mauritius	Up Middle	Sub-Saharan Africa
Brazil	Up Middle	Latin America & Caribbean	Mexico	Up Middle	Latin America & Caribbean
Bulgaria	Low Middle	Europe & Central Asia	Mongolia	Low	East Asia & Pacific
Burkina Faso	Low	Sub-Saharan Africa	Morocco	Low Middle	Middle East & North Africa
Burundi	Low	Sub-Saharan Africa	Mozambique	Low	Sub-Saharan Africa
Cambodia	Low	East Asia & Pacific	Namibia	Low Middle	Sub-Saharan Africa
Cameroon	Low	Sub-Saharan Africa	Nepal	Low	South Asia
Canada	Up Higher	North America	Netherlands	Up Higher	Europe & Central Asia
Cape Verde	Low Middle	Sub-Saharan Africa	New Zealand	Up Higher	East Asia & Pacific
Chile	Up Middle	Latin America & Caribbean	Nicaragua	Low	Latin America & Caribbean
China	Low Middle	East Asia & Pacific	Niger	Low	Sub-Saharan Africa
Colombia	Low Middle	Latin America & Caribbean	Nigeria	Low	Sub-Saharan Africa
Congo	Low	Sub-Saharan Africa	Norway	Up Higher	Europe & Central Asia
Costa Rica	Up Middle	Latin America & Caribbean	Pakistan	Low	South Asia
Côte d'Ivoire	Low	Sub-Saharan Africa	Panama	Up Middle	Latin America & Caribbean
Croatia	Up Middle	Europe & Central Asia	Paraguay	Low Middle	Latin America & Caribbean
Cyprus	Low Higher	Europe & Central Asia	Peru	Low Middle	Latin America & Caribbean
Czech Republic	Up Middle	Europe & Central Asia	Philippines	Low Middle	East Asia & Pacific
Denmark	Up Higher	Europe & Central Asia	Poland	Up Middle	Europe & Central Asia
Dominican Republic	Low Middle	Latin America & Caribbean	Portugal	Up Higher	Europe & Central Asia
Ecuador	Low Middle	Latin America & Caribbean	Romania	Low Middle	Europe & Central Asia
Egypt	Low Middle	Middle East & North Africa	Russian Federation	Low Middle	Europe & Central Asia
El Salvador	Low Middle	Latin America & Caribbean	Rwanda	Low	Sub-Saharan Africa
Estonia	Up Middle	Europe & Central Asia	Saudi Arabia	Up Middle	Middle East & North Africa
Ethiopia	Low	Sub-Saharan Africa	Slovakia	Up Middle	Europe & Central Asia
Fiji	Low Middle	East Asia & Pacific	Slovenia	Low Higher	Europe & Central Asia
Finland	Up Higher	Europe & Central Asia	South Africa	Low Middle	Sub-Saharan Africa
France	Up Higher	Europe & Central Asia	Spain	Up Higher	Europe & Central Asia
Gambia	Low	Sub-Saharan Africa	Sri Lanka	Low Middle	South Asia
Georgia	Low	Europe & Central Asia	Sudan	Low	Sub-Saharan Africa
Germany	Up Higher	Europe & Central Asia	Suriname	Low Middle	Latin America & Caribbean
Ghana	Low	Sub-Saharan Africa	Sweden	Up Higher	Europe & Central Asia
Greece	Up Higher	Europe & Central Asia	Switzerland	Up Higher	Europe & Central Asia
Guinea	Low	Sub-Saharan Africa	Tajikistan	Low	Europe & Central Asia
Guinea-Bissau	Low	Sub-Saharan Africa	Togo	Low	Sub-Saharan Africa
Honduras	Low Middle	Latin America & Caribbean	Trinidad and Tobago	Up Middle	Latin America & Caribbean
Hungary	Up Middle	Europe & Central Asia	Tunisia	Low	Middle East & North Africa
India	Low	South Asia	Turkey	Low Middle	Europe & Central Asia
Indonesia	Low	East Asia & Pacific	Turkmenistan	Low Middle	Europe & Central Asia
Iran (Islamic Republic of)	Low Middle	Middle East & North Africa	Ukraine	Low	Europe & Central Asia
Ireland	Up Higher	Europe & Central Asia	United Kingdom	Up Higher	Europe & Central Asia
Israel	Low Higher	Middle East & North Africa	United States of America	Up Higher	North America
Italy	Up Higher	Europe & Central Asia	Uruguay	Up Middle	Latin America & Caribbean
Jamaica	Low Middle	Latin America & Caribbean	Venezuela	Up Middle	Latin America & Caribbean
Japan	Up Higher	East Asia & Pacific	Yemen	Low	Middle East & North Africa
Jordan	Low Middle	Middle East & North Africa	Macedonia	Up Middle	Europe & Central Asia
Kazakhstan	Low Middle	Europe & Central Asia			

Appendix C. Data used in SIMPLE

Variables	Permanent Croplands	Crop Production		Crop Price	Urban lands	Input Cost Share: Land in Crop Sector
Source of data	FAOSTAT (2011)				Angel et al. (2010)	GTAP (V.6)
Units	1000 hectares	million metric tonnes corn-equivalent	million USD: 1999-2001 prices	USD: 1999-2001 prices	1000 hectares	in %
By Geography						
East Asia & Pacific	265241	1722	182532		10828	18
Europe & Central Asia	350493	1251	132606		17499	26
Latin America & Caribbean	155009	689	73034		8949	9
Middle East & North Africa	49368	200	21200	106	2258	18
North America	230211	717	76002		12373	26
South Asia	205137	838	88828		3903	18
Sub-Saharan Africa	144979	361	38266		2296	9

Variables	Population	Per Capita Real GDP	Crop Utilization by Sector			Input Cost Shares		
			Food Sector	Livestock	Processed Food	Crops in Biofuels	Crops in Livestock	Crops in Processed Foods
Source of data	UN World Population Prospects: The 2008 Revision	WDI (2011)	FAOSTAT (2011)			GTAPBIO (V.6)	GTAP (V.6)	
Units	million	billion constant 2000 USD	%					
By Per Capita Income								
Upper high	856	28705	30	31	39		4	9
Lower high	9	17051	45	33	21		7	9
Upper middle	494	4933	20	14	65		7	18
Lower middle	2090	1446	53	18	29		16	25
Low	2142	472	53	6	41		24	21
Global						0.75		

Appendix D. Parameters used in SIMPLE

Commodity/ Region	Price elasticities		Income elasticities		Elasticity of substitution in crop production		Price elasticity				Conversion factor of urban to cropland
							Non-land		Land		
	Intercept	Slope	Intercept	Slope	Starting Value	Calibrated Value	- 5 Year	- 15 Year	- 5 Year	- 15 Year	
Source of data	Calculated from Muhammed et al (2011)				Keeney and Hertel (2005)				Ahmed, Hertel & Lubowski (2008) and Gurgel, Reilly & Paltsev (2007)		USDA (2009), Liu & Tian (2010), Weber & Puissant (2003)
By Commodity											
Crops	-0.74	0.07	0.88	-0.10							
Livestock	-0.83	0.05	1.05	-0.09							
Processed Foods	-1.17	0.08	1.20	-0.10							
Non-Food	-1.14	0.04	1.56	-0.05							
By Geography											
East Asia & Pacific									0.04	0.11	0.46
Europe & Central Asia									0.04	0.11	0.23
Latin America & Caribbean									0.20	0.55	0.23
Middle East & North Africa									0.11	0.29	0.39
North America									0.04	0.11	0.23
South Asia									0.10	0.28	0.46
Sub-Saharan Africa									0.20	0.55	0.39
Global					0.43	0.55	0.49	1.34			

Appendix E. Shocks used in model calibration and in historical validation (in % cumulative change)

Model Calibration: 2001 to 2006 [5-years]							
By Income	**Population**	**Per Capita Income**	**Biofuels**	**Urban land cover**	**TFP: Crop**	**TFP: Livestock**	**TFP: Proc. Food**
Upper high	3.39	7.48				2.02	
Lower high	11.11	9.32				2.02	
Upper middle	5.87	13.99				4.06	3.75
Lower middle	3.78	42.46				11.49	
Low	8.12	27.54				1.51	
By Geography							
East Asia & Pacific				19.27	7.65		
Europe & Central Asia				6.98	6.05		
Latin America & Caribbean				15.16	7.35		
Middle East & North Africa				15.90	5.85		
North America				12.65	6.45		
South Asia				17.01	6.15		
Sub-Saharan Africa				23.35	3.10		
Global			118.22				
Historical Validation: 1961 to 2006 ("Backward" Validation: 2006 to 1961) [45-years]							
By Income	**Population**	**Per Capita Income**			**TFP: Crop**	**TFP: Livestock**	**TFP: Proc. Food**
Upper high	42.2 (-29.7)	221.6 (-68.9)				24.5 (-19.7)	
Lower high	222.8 (-69)	230.4 (-69.7)				24.5 (-19.7)	
Upper middle	151.6 (-60.2)	113.9 (-53.3)				75.8 (-43.1)	281.7 (-73.8)
Lower middle	114.6 (-53.4)	558.9 (-84.8)				129.8 (-56.5)	
Low	170.9 (-63.1)	192.5 (-65.8)				16.9 (-14.4)	
By Geography							
East Asia & Pacific					221 (-68.9)		
Europe & Central Asia					119.5 (-54.5)		
Latin America & Caribbean					195.4 (-66.2)		
Middle East & North Africa					111.2 (-52.7)		
North America					138.4 (-58.1)		
South Asia					124 (-55.4)		
Sub-Saharan Africa					38.7 (-27.9)		

Appendix F. Global results of the "Backward" Validation and Model Calibration

Variable	Total Effect: "Backward" Validation 2006 to 1961	Total Effect: Model Calibration 2001 to 2006
Agricultural Variables		
Crop Price	49.6	4.9
Crop Output	-72.5	10.9
Cropland	-14.6	1.1
Crop Yield	-67.8	9.7
Crop demand		
Food	-65.1	8.4
Feedstuff	-68.4	3.0
Raw Materials	-84.5	15.3
Food demand		
Livestock	-56.8	8.5
Processed Food	-79.0	12.7