Looking back to move forward: Evaluating global agricultural land use in integrated assessment models

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Integrated Assessment Models (IAMs) are indispensable in the debate over climate change impacts and mitigation policies. Recently these models have incorporated land-based mitigation policies into their analyses. This is important, since land-based emissions account for more than one-quarter of global GHG emissions (Baumert, Herzog, and Pershing 2009), 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 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 IAMs have been notably lacking to date.

Currently, there is great interest in redressing this limitation. However, the challenge is a daunting one, since IAMs seek to integrate not only climate, and the responses of the biophysical system to climate change, but also the economic impacts of such changes. Unlike climate models, economic 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 2012). This suggests a useful way forward for the IAM community.

Without doubt, the most important fact about global land use 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, Davis, and Lobell 2010). Whether or not this historical performance can be replicated in the future is a central question in IAM analysis (Havlik et al. 2012; Wise et al. 2009). Yet, to our knowledge, none of the IAMs currently in use is capable of reproducing this historical experience endogenously. Indeed, it is not uncommon for IAMs to treat crop yields as an exogenous trend (Calvin et al. 2012), thereby *pre-determining* the answer to this important question.

We propose that land-based IAMs be asked to evaluate their models by looking back at this historical experience. In this paper, we illustrate the opportunity and the challenge of undertaking such an historical validation exercise using the SIMPLE model of global crop production. As its name suggests, this framework is designed to be as simple as possible while capturing the major forces at work in determining global crop land use. This makes it a useful test-bed for the design of validation experiments. We test the model's performance against the historical period: 1961-2006, illustrating what it does well and what it does poorly. Using this 45-year period as our laboratory, and focusing on the dimensions along which the model performs well, we then explore how various model restrictions which appear in the IAM literature alter the model's historical performance. This serves to highlight which areas of IAM development are likely to be most important from the point of view of global land use change. We conclude with suggestions about how best to advance the state of our knowledge about IAMs by testing these models against history.

The SIMPLE model

Figure 1 outlines the structure of SIMPLE. A complete listing of equations and parameter values is provided in the SOM. SIMPLE's components can be divided between those contributing to the global demand for crops and those contributing to global crop supply. At the core of the supply-side are 7 regional production functions generating crop output for the following continental scale regions: East Asia & Pacific, Europe & Central Asia, Latin America & Caribbean, Middle East & North Africa, North America, South Asia and Sub-Saharan Africa. These are calibrated to reproduce current yields in each region, as reflective of the existing technology, inherent land productivity, and non-land input use. Changes in any of these underlying factors will result in altered crop yields.

We refer to the potential for increasing yields by applying more non-land inputs in response to land scarcity as the '*intensive margin of supply response*' which is governed by the elasticity of substitution between land and non-land inputs: σ_{CROP} (Keeney and Hertel 2008). In contrast, the '*extensive margin of supply response*' is governed by the elasticities of supply of land and non-land inputs to the crops sector: ε_{LAND} and ε_{NLAND}, which we set to their regional and long run values for this validation exercise (Keeney and Hertel 2005; Ahmed, Hertel, and Lubowski 2008; Gurgel, Reilly, and Paltsev 2007). Cropland conversion from pasture or forests carries with it potential GHG emissions, which vary by geographic location (Plevin et al. 2011). Over the long run, changes in technology serve to shift the regional crop product supply schedules outward, so that more crop products will be delivered at a given market price and level of land and non-land input use.

The global demand for crop output is comprised of feedstocks for biofuels (exogenous in our model) as well as direct food consumption by households, feedstuffs for livestock and crop inputs to processed food production. Livestock and processed foods are value-added products and are conceptualized in this crop model as being produced and consumed within each demand region using crop and non-crop inputs. In our baseline, income levels differ across the 5 consuming regions, based on their categorization by the World Bank in 2001: low income countries (including India), lower middle income countries (including China), upper middle income nations (including Brazil), lower high, and upper high income countries. A large share of crop demands in SIMPLE are *derived demands*, originating from the consumer demands for livestock and processed products. This is important, since technological change and factor substitution in these sectors can alter the intensity of crop use in producing these food products. The ability of the livestock and food processing sectors to conserve on crops in response to higher prices is captured by the elasticities of substitution between crop and non-crop inputs used in these sectors: σ_{LSTK} and σ_{PRFD}.

The demand for food in the income regions is a function of population, per capita income and commodity prices. The latter are governed by the income and price elasticities of demand, $\varepsilon_{iY}(y)$ and $\varepsilon_{iP}(y)$, which vary by commodity type (crop, livestock, processed foods) as well as consumers' income level (Muhammad et al. 2011). In particular, food demands in regions with high per capita incomes are less responsive to changes in both income and prices, whereas low income consumers have little choice but to reduce consumption when food prices rise, since food makes up a relatively large share of their household's budget, and they tend to respond to higher incomes by consuming more food and upgrading their diets.

Finally, long run equilibrium in SIMPLE is attained when global crop supply equals global demand where the equilibrating variable is the global crop price.

Model adjustments

While most of its component parts are based on econometric estimates of key parameters, as with any global model, some tuning is necessary in order to ensure reasonable performance of the full equilibrium model. However, we refrain from tuning the model over the same period for which the validation is undertaken. Instead, we focus on the period 2001-2006 for tuning purposes. This was a period during which global economic growth was strong, output and prices were rising and global land use was expanding. We focus the model tuning on two key dimensions of the derived demand for crop products. The first relates to the unobserved intensification parameters in the livestock and food processing sectors for which we do not have robust estimates. Accordingly, we 'calibrate' these parameters by focusing on the high income region and choosing the parameter which best fits the data on crop input use over this period. This value is subsequently assigned to all demand regions. We also adjust the estimated relationship between per capita income and the price and income elasticities of demand, which remains uniform for all demand regions in the model, as the original estimates give rise to excessive growth in the global direct demand for crops over this period. Details regarding the tuning process are outlined in the SOM.

Model validation

Given our interest in long run projections of global land use change (e.g., 2050), we choose to evaluate the SIMPLE model over a comparable period of time – in this case from 1961 to 2006[1]. The most obvious metrics involve comparing endogenous predictions to observed changes in the following global scale variables: (a) crop production, (b) crop price, (c) cropland area, and (d)

[1] 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 principle, we prefer the backwards approach (i.e. going from 2006 back to 1961). However, in practice we found this very confusing. Therefore, we first simulate the model backwards to 1961, thereupon establishing an historical equilibrium. We then undertake the validation experiment by simulating the model forward again to 2006, comparing these results to the observed changes over this period.

average crop yield. To derive these endogenous changes in SIMPLE, we perturb the model 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 1. Looking at the table, we see that population and per capita incomes grew steadily during this historical period. Notable growth in population can be observed in the low high, upper middle (such as Brazil) and low income regions (such as India). Likewise, we observe steady growth in per capita incomes with the low 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 1.15% per annum, with the exception of Sub-Saharan Africa where it grew by 0.9% annually. With regard to the livestock sector, we observe strong TFP growth in the low middle income region. In contrast, livestock TFP growth in the low income region grew by only 0.2% per annum. Due to lack of reliable regional estimates, we imposed a uniform rate in the TFP growth in the processed food sector across all regions.

Key global validation results are reported in Figure 2 (see SOM for details). From the figure, we see that SIMPLE slightly overstates the global change in crop production over the 1961-2006 period (206% vs. 196%). The model also slightly understates the historical decline in crop price (24% vs. 29%). 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 (17% and 162%, respectively) slightly above the observed values (16% and 156%, respectively) due to the higher level of global output. Overall, we are pleased with these global results and we will draw on them in the next section to explore the implications for assessing existing IAMs.

The regional results are much less satisfactory, indicating that the model has a hard time predicting how much each region would contribute to the global output expansion over the 1961-2006 period. Figure 3 reports the simulated and actual changes in crop production, average crop yield and crop land use in each geographic region. The East and Asia Pacific region is the only one where the simulated changes in production closely follow the historical data. For average crop yields, the model does well in simulating changes in the Latin America & Caribbean, Middle East & North Africa and North America regions. However, SIMPLE grossly understates the increases in crop yields in the South Asia and Sub-Saharan Africa regions, while overstating yield increases in Europe and Central Asia. These divergences are, in turn, evidenced in divergences in regional crop land changes (bottom panel of Figure 3). In some regions, the simulation shows crop land expansion but in reality crop land use actually contracted during this historical period[2].

Many of these regional divergences may have been driven by institutional and socio-political factors which are not incorporated in SIMPLE. But within our framework, we have identified several potential sources of regional divergences. The first of these stems from our assumption that technological progress is 'neutral' in the sense that it affects the incentive to use all inputs equally. However, in South Asia, the green revolution was biased towards increased variable input usage, as the technology package accompanying the new hybrid wheat and rice varieties required massive increases irrigation and fertilizer applications. Indeed, in his analysis

[2] In SIMPLE, croplands are based on FAO data on arable land plus permanent croplands. However as argued by Fuglie and Rada (2012), this data may not fully reflect the actual changes in land area under crop cultivation for some countries over this historical period.

period of agricultural output growth over the green revolution, Fuglie (2012) suggests that most of the increase in output can be attributed to increased input use, not increases in TFP. In order to capture this effect, we would need estimates of the input-bias associated with technological progress over this period of time.

A second source of the SIMPLE model's regional divergences in production, yield and land use is the naïve assumption of globally integrated markets. This is far from the truth in the current world economy, and it was much further from reality throughout most of our 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 1991). In this work, Johnson discusses the many distortions which caused the global distribution of agricultural output to be inconsistent with economic logic. These distortions have 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 WTO, agricultural support has been reformed in many parts of the world. However, there remain significant barriers to free trade in agricultural products (Anderson and Martin 2005). Without explicitly modeling these trade policies and their evolution through time, it is difficult to predict where global agricultural output will expand in the future, and the absence of explicit trade policies in SIMPLE no doubt plays an important role in the model's poor regional predictive ability.

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, and 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, as its share in global trade of agricultural products has declined by around 70% during this same period (FAO 2013).

In summary, our validation experiment suggests that, while SIMPLE is adept at capturing changes in output and land use at global scale, the problem of allocating these long run changes across regions is far more challenging – a topic to which we will return in the discussion section. In light of these findings, we will restrict our analysis in the subsequent session to global scale variables.

Evaluating the State of the Art in Global Integrated Assessment Modeling

Existing global economic models produce significantly different projections of global land use in 2050 (Schmitz et al. in review). This is hardly surprising, given the widely varying assumptions imbedded in their models. Some of these differences may be inconsequential for the estimated 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. Furthermore, when the IAM developers add a new feature, there is no way of objectively measuring whether it has actually improved the predictive ability of the model. For this reason, we believe that having a standard set of validation experiments against which to evaluate model performance, as well as to test specific features, and set future research priorities, would be invaluable.

In this section, we introduce just such a set of experiments, each focusing on a specific restriction to the SIMPLE model, aimed at highlighting the consequences for global land use change. These restrictions have been chosen to highlight shortcomings in existing IAMs, allowing us to assess their relative significance. They include: fixed 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, we also consider two experiments (E6.a and E6.b) which include elements of the earlier experiments.

Figure 4 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 our original historical baseline. We first look at restrictions in the way crop demand is modeled. We start with the simplest possible assumption, namely that of maintaining per capita food consumption at historical levels as is done in some IAMs (Wise et al. 2009; Calvin et al. 2012). As illustrated in Figure 4, imposing fixed 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 crop land actually contracts.

A more common consumption specification in IAMs is to have fixed (unchanging) price and income elasticities of food demand (Havlik et al. 2012; Nelson et al. 2010). In this case, rather than becoming smaller in absolute value as per capita incomes rise (recall Figure 1) (Muhammad et al. 2011), the responsiveness of demand to rising incomes is based on historical estimates of these values and are kept constant (E2). In this case, we observe in Figure 4 that 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 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.

Let us now turn from the demand to 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 (additional yield). We begin with the parameters which influence the extensive margin. Specifically, in E3 we replace the long-run supply elasticities for land and non-land inputs with their corresponding short-run (five year) values as were used in our 2001-2006 tuning exercise. While we cannot link this with any particular IAM, we suspect that those models based on econometric estimates of crop land area response are likely to fall prey to this limitation. This is because most such estimates are based on annual time series data from which it is hard to extract extremely long term supply response. This point is emphasized by Hertel (2011) who offers indirect evidence that prominent global studies of biofuels (Fischer et al. 2009) and climate impacts (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 rising crop prices over this period, as crop land area is unable to respond as vigorously to increased demand for crop production. While yield changes are comparable to their historical values over this period, production falls short of it historical value, despite the rising crop prices.

The other critical component of supply response 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 and Schlenker 2011; Keeney and Hertel 2009; Huang and Khanna 2010; Goodwin et al. 2012), there is little doubt that significantly higher prices do encourage farmers to respond with more intensive cultivation techniques. Yet not all IAMs incorporate this possibility (Calvin et al. 2012), and it is often unclear how large this effect is in those that IAMs do allow for endogenous yield response. We explore this issue in experiment E4 which eliminates this intensive margin of supply response. As a consequence, yields grow more slowly than in the historical record – being driven solely by TFP growth. Crop prices are essentially flat and crop land 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 crop land requirements.

A slightly different wrinkle on the matter of exogenous yields involves explicitly targeting the rate of average crop yield growth (as opposed to targeting Total Factor Productivity). Note that in some IAMs, productivity growth is primarily reflected through crop yields (Lotze-Campen et al. 2008). Of course, if we knew in the future how fast yields were to grow, one can expect that we have made one major step closer to our goal of making credible projections of global land use change. But, as experiment E5 demonstrates, even knowing yields with certainty would not allow us to predict crop land change. Since land is only one of many agricultural inputs, and accurately projecting yields does allow for an accurate prediction of the change in crop prices over time, as can be seen from the lower right hand panel in Figure 4.

The last two experiments illustrate the potential impacts in our historical projections when we combine some of the above restrictions. We start with a biophysical view of the historical period wherein per capita food consumption is fixed, 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 our first experiment, we observe that global crop production is understated (upper left panel of Figure 4). By targeting average yields and ignoring the economic yield response, we see that the changes in global cropland use and global crop price move in the opposite direction of what was observed historically.

Another interesting combination of restrictions is captured by E6.b, which seeks to mimic the behavior of global economic models which fail to account for long run changes on the demand and supply sides. Specifically, we do not allow the price and income elasticities of demand for food to evolve with per capita incomes, and we use the five-year input supply elasticities. With a overly responsive demand for food, our projections tend to overstate the rise in global crop production while understating the reduction 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 crop land expansion is understated under this scenario.

Summary and Conclusions

As Integrated Assessment Models (IAMs) are broadened to encompass changes in agricultural land use, it is important to test their performance against history. In this paper, we present such an analysis by looking back at the historical period 1961to 2006 – an era in which crop output tripled, while cropland area expanded by less than 20%. To conduct this validation experiment, we use SIMPLE, a parsimonious model of the global crops sector. Using the key historical drivers of global agriculture during this period, namely population, incomes and TFP, we find that SIMPLE is able to accurately reproduce changes in crop price, production, cropland use and average crop yields at global scale. However, results at the regional level are less favorable, highlighting the challenge of predicting the distribution of cropland expansion across the globe. We believe that these divergences are influenced by institutional and socio-economic policies during this historical period. However, they also likely highlight the limitations of the underlying assumptions of our framework. In particular, it is likely that the different sources of productivity growth in each region, our assumption of fully integrated world markets, and the presence of trade barriers may have driven these regional divergences in crop production, cropland use and average crop yields.

After validating the model at global scale, we turn to an investigation of how the specific assumptions imbedded in many IAMs influence the results of this historical exercise. We find that those models which are largely biophysical – ignoring the price responsiveness of demand and supply likely understate changes in crop production, while overstating price changes. Many of the models which do incorporate economic responses do so based on annual time series estimates which likely understate long run responses to price changes. We find that when these shorter run assumptions are imposed on SIMPLE, the model tends to over-predict historical output changes, while understating land use change. By identifying which restrictions matter most for a given variable of interest (e.g., global crop land change). IAM scientists can help to prioritize which areas of improvement are of highest priority in their research program.

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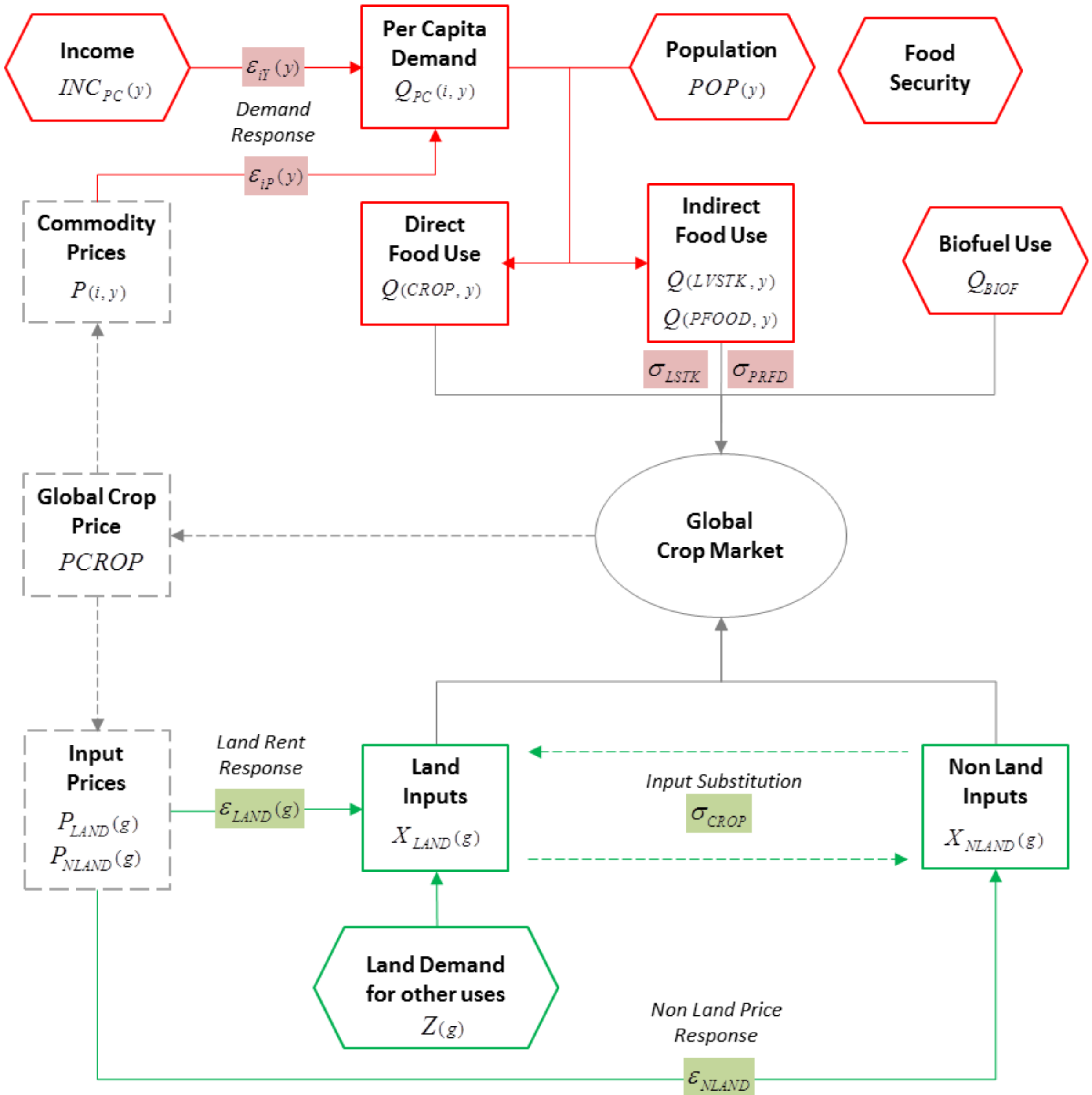

Figure 1. Overview of SIMPLE: The bottom panel (green) refers to supply regions for the aggregate crop commodity which are indexed by continent. The upper panel refers to demand regions, indexed by income level. The disposition of crops includes direct consumption, feedstuff use and food processing, as well as biofuels. Adjustment of price in the global crop market ensures that long run supply equals long run demand.

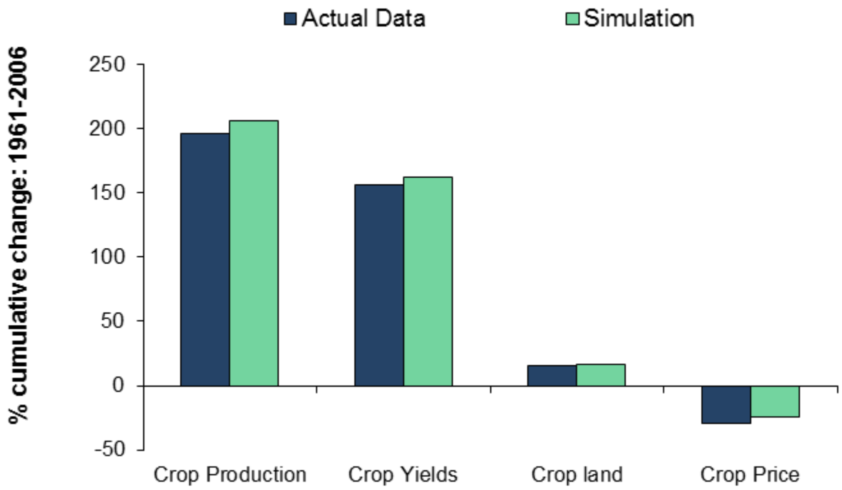

Figure 2. Global results of the historical validation experiment (1961 to 2006). The bars show the percent changes in (from left to right) global crop production, yield, land use and price computed from actual data (dark blue bar) and from the simulation results (light green bar). The historical experiment is conducted using the SIMPLE model given exogenous historical growth in population, per capita income and total factor productivity growth in agriculture after calibrating the model over the 2001-2006 period.

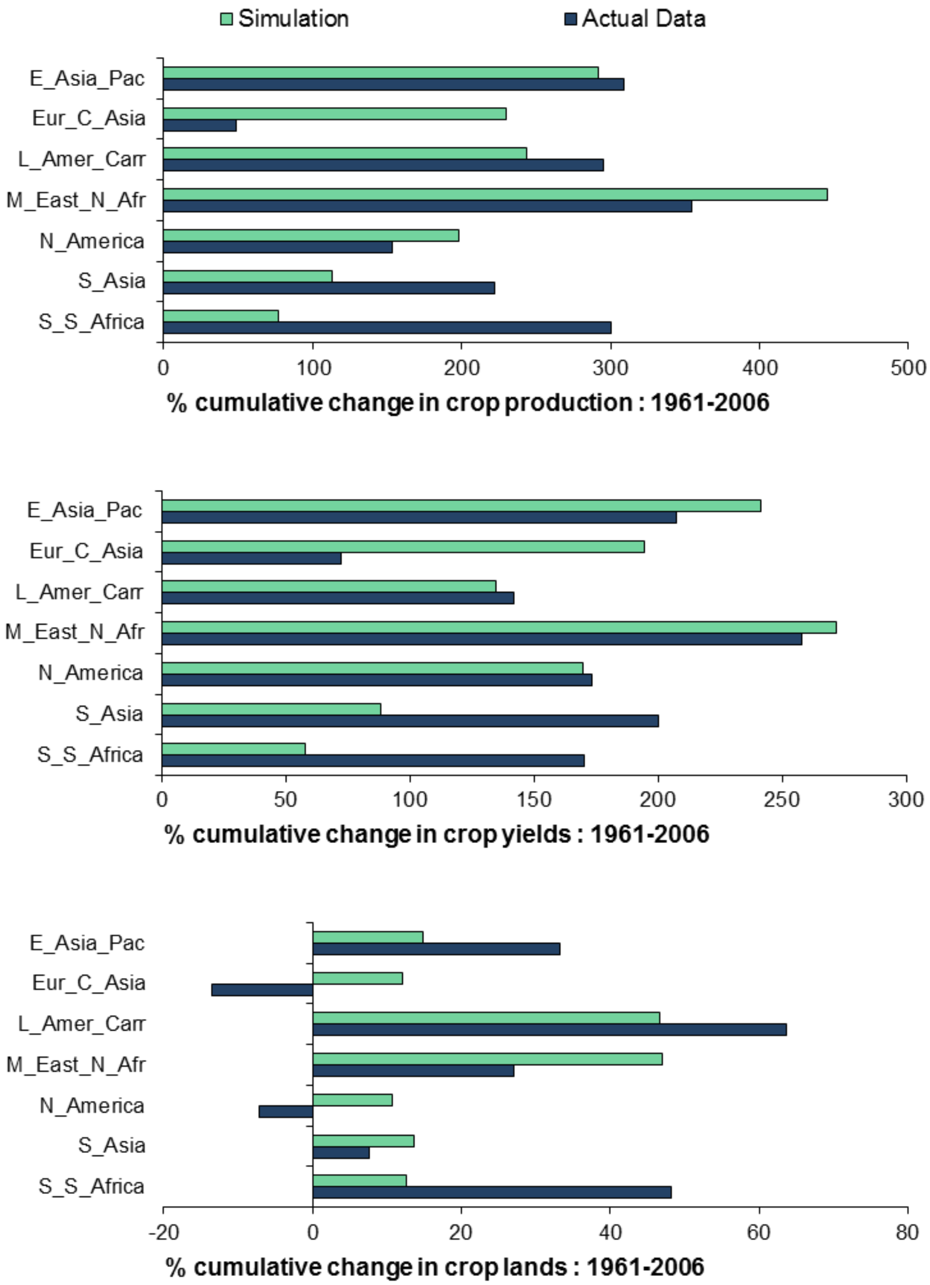

Figure 3. Results of the historical validation experiment (1961 to 2006) by geographic regions. The panels show the percent changes in (from top to bottom) crop production, yield and land use computed from actual data (dark blue bar) and from the simulation results (light green bar). Geographic regions in SIMPLE consists of (from top row to bottom row) East Asia & Pacific, Europe & Central Asia, Latin America & the Caribbean, Middle East & North Africa, North America, South Asia, and Sub-Saharan Africa

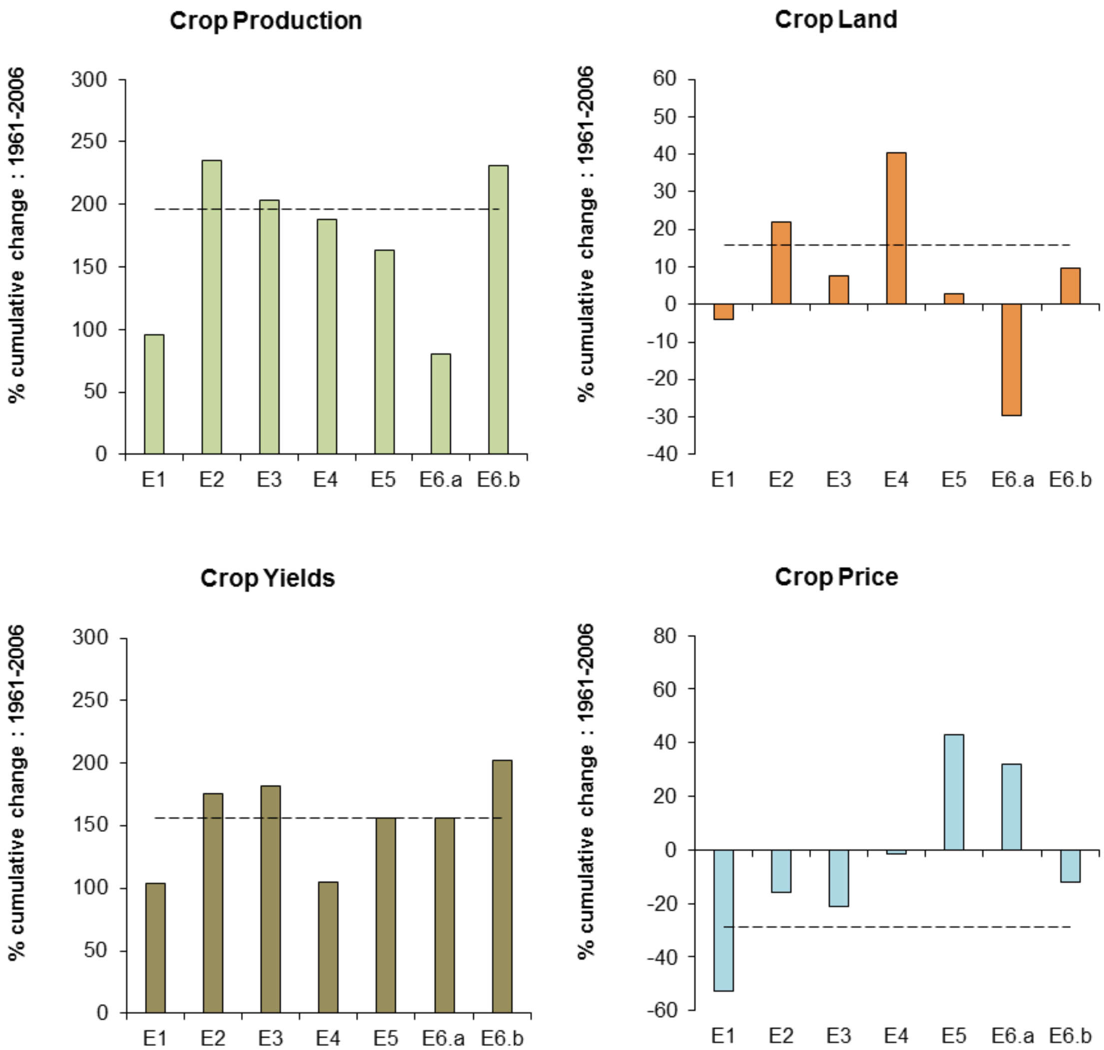

Figure 4. Global results of the evaluation experiments (1961 to 2006). The panels show the percent changes in crop production (upper left), yield (lower left), land use (upper right) and price (lower right) computed from actual data (dashed line) and from the simulation results (colored bars). The experiments consists of (starting from E1 up to E6.b) Fixed per capita consumption, Fixed food demand response, Restricted extensive margin, Restricted intensive margin, Targeted crop yield, Combined fixed per capita consumption, restricted intensive margin and targeted crop yields, and Combined fixed food demand response and targeted crop yields.

Table 1.Per annum growth rates of exogenous drivers for the historical period 1961 to 2006

Income Regions	Population	Per Capita Income	TFP: Livestock			Geographic Regions
			Livestock	Processed Food	Crops	
Up Higher	0.79	2.62	0.92		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	0.74	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