Policy Decisions and Climate-Smart Agriculture in Africa

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Abstract

Increasing the agricultural production in Africa is vital to the well-being of a growing population. At the same time, reducing greenhouse gas emissions from agriculture, and halting land use change as a driver of deforestation, is vital to meeting climate goals. As part of project undertaken between Climate Interactive and Mohammed VI Polytechnic University, we have constructed a national-level model grounded in existing data and research, and calibrated to data and published strategies for Ethiopia. Our simulation will allow stakeholders to see what national policies work in meeting the dual goals of more food and lower emissions. Early results already highlight some core principles of Climate Smart Agriculture policy, which reinforce longstanding lessons of system dynamics:

- *The need to change long-term trends in land and livestock growth*
- *The need to control both the amount AND the emissions intensity of agriculture*
- *How efficiency and yield improvements allow countries to slow the growth of land use and livestock*
- *How growth in demand will eventually overwhelm any gains*

We plan further work to better capture carbon in soil and biomass, and resilience.

Key Words: Agriculture, Climate, Smart, Policy, Decision Support

1. Introduction

A major transition of agriculture in Africa is vital for several reasons. Food production must increase to serve a growing African population – already twenty percent of African people are undernourished (FAO 2015) and population is expected to double to 2.4 billion by 2050 (UN Population 2015). At the same time, millions of farmers are aspiring to greater incomes and improved livelihoods, and growth in agriculture is part of the solution. There is likely to be greater demand on African agriculture as part of feeding the world as well (FAO 2009). This presents an opportunity to develop Africa's economy, increase employment, and decrease poverty. At the same time agricultural production may be difficult to increase because rainfall and drought trends are getting worse due to climate changes, and because human activity, if not designed intelligently can drive the land and natural resources to scarcity

Production has to increase at the same time as the negative impacts of climate change are already being felt in Africa, and are likely to become worse. Both lower average yields and the incidence of extreme events are having increasing harm to food security (World Bank 2013). Climate change has to be kept to a level where adaptation is even possible, and African nations are going to be part of the solution.

African nations are presenting Nationally Determined Contributions (NDCs) where agriculture is an important part of emission reductions. In Africa, agriculture represents larger percent of greenhouse gas emissions than it is in the rest of the world (see figure 1). There is an important interaction between agriculture and land use, which also represents a large share of greenhouse gas emissions. So the increase in production, necessary as it is for livelihoods, has to be achieved while keeping deforestation in check, not increasing emissions from agriculture, and conserving the existing land resources. Decision-makers need to understand the complexities of meeting these three goals.

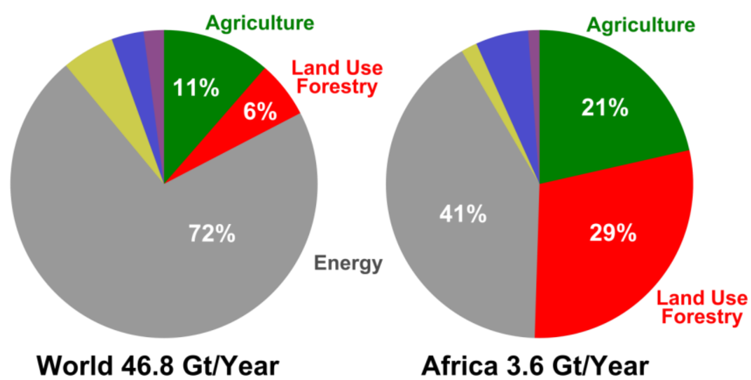

Figure 1: World and Africa GHG Emissions by sector (source WRI 2017)

Many African countries have been implementing national agricultural policies to increase agricultural productivity, have sustainable production growth, and protect land resources from desertification. These policies include the choice of crop species and livestock species that are available to farmers, encouraging industrialization and modern land practices, and encouraging more or more efficient fertilizer use. These changes in turn can improve yields, emission factors, or other intermediate variables to result in desired outcomes.

For example, Ethiopia's Climate Resilient Green Economy Strategy (Ethiopia 2015a) lays out actions and goals to increase both livelihoods and resilience while not increasing emissions. While the goal of this project is a simulation adaptable to any developing economy, Ethiopia's documents are clear enough to serve as a first case. The simulations presented in this paper are calibrated to Ethiopia data and based on its proposals. This is not meant to be an endorsement of the Ethiopia plan, merely that the documents are useful as source for modeling.

Ethiopia sets forth its plan over several documents: the beginning of the plan (Ethiopia 2011), its main strategy (2015a) and its Individual Nationally Determined Contribution (INDC) (2015b) and its Communications to the UNFCCC (2016). Data are also taken from the UN Food and Agriculture Organization (FAOSTAT 2017). The plans set out sector goals for reductions below BAU for emissions along with some specific actions to achieve them. As shown in Figure 2, Ethiopia's goal is to have agricultural emissions grow from 75 to 95 Mt CO_2eq, 90 Mt lower that the BAU projection of 185 Mt CO_2eq. At the same time, there would be enough reduction in land used for agriculture that forestry would be a net 40 Mt CO_2eq removal – 130 Mt lower than the projected growth from 55 to 90 Mt CO_2eq. From these and the stated goals for growth in agricultural output, we derive the dual reference mode shown in Figure 3. Given that the goals for food available is growth to meet demand, and for GHG emissions from agriculture is to be lower than BAU, we ask where within possible futures the proposed policies will actually lead.

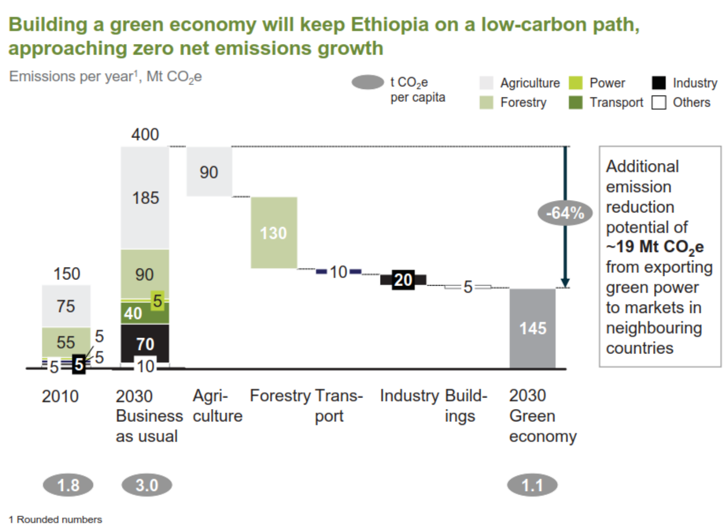

Figure 2: Emission Reduction Goals from Ethiopia (2011)

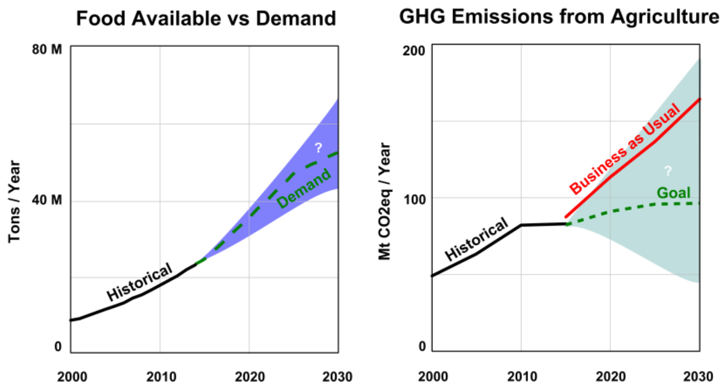

Figure 3: Reference Modes for Food and Emissions

System dynamics as a field has uncovered important lessons that are clearly applicable to the transformation of African agriculture. SD models have been used to assess sustainable and ecological adaptation strategies in agriculture at the local levels of districts, by simulating the dynamics between the farmers' economic system (Chapman & Darby 2016), or to simulate the material and energy flow in the local industry chain (Li et al 2012).We embark on this project particularly with *Limits to Growth* (Meadows et al 2004) in mind. We know that exponential growth in population and living standards will eventually overwhelm bounded improvements in yield, efficiency, and emission factors. Yet it is important to make these improvements and not wait for the demographic transition. Even as Africa needs to adapt to unavoidable climate changes, we wish to make sure adaptation does not crowd out mitigation to avoid even worse changes. Our goal for the simulation is to help countries with practical policy choices while teaching the core lessons of systems and sustainability.

The framework we use is Climate Smart Agriculture (CSA), which is built around three pillars: food security through development, resilience to climate-related changes, and mitigation of emissions (FAO 2010). The framework includes the importance of short-term adaptation not crowding out long-term needs for mitigation. Our dynamic hypothesis is that the operation of a balancing loop that attempts to increase food in response to rising demand has the maladaptive effect of increasing emissions; and that CSA practices can substitute for growth, hopefully until growth can be brought under control. The underlying causal loop diagram of our hypothesis is shown in figure 4.

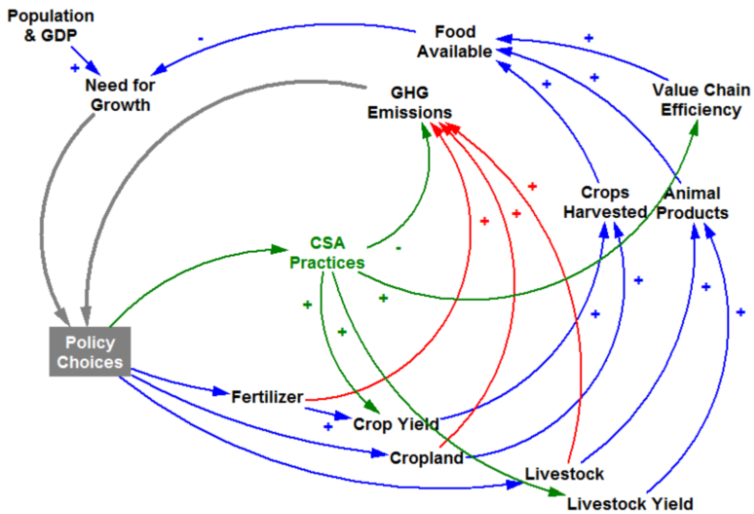

Figure 4: Causal Loop Diagram of the Logic of CSA

The causal loop in figure 4 represents the meta-model / broad view of our model and the complete model analyses in more details the relationships between the different variables and other intermediate variables. The next section will present in details the different parts of the model, namely the demand, land, production, Food Available and the emissions sectors. For the Ethiopian case, the model user has to set a limited number of nine policies, related to value chain efficiency, CSA practices and fertilizer use that are detailed in section 2. The way we calibrated the model to historical data is explained in section 3. Finally, experiments with the model are shown in section 4, and demonstrate how the simulation can be used to design an efficient mix of the considered nine policies for the Ethiopian case to meet the desired goals in terms of food security and greenhouse gas emissions.

2. Model Description

The purpose of this simulation is to allow stakeholders to test policies or sets of policies and observe results in terms of food and GHG emissions. In the tradition of Climate Interactive's other simulations, this project is a simulation for exploring options and their outcomes. Instead of a fully endogenous model of the agricultural system, we have produced a simulation environment for evaluating choices. In summary, the simulation uses population and GDP to create demand. Then the user forms part of the feedback loop, making the Policy Choices shown in figure 4 above, making choices about land, livestock, and agriculture practices in order to meet demand. The simulation enforces physical restraints and, the user can observe the results on both food availability and climate impacts.

The simulation is created in Vensim. The complete model file, with supporting data, is available as a supplement to this paper. Part of the design conditions is that the model be able to run on free versions of Vensim and be translatable to other platforms, so that the simulation can be shared with partners outside the SD field.

a) Demand Sector

In this simulation we define demand as a value representing desired standards for domestic food consumption met by either production (after losses and exports) or imports. The specific level of demand is relative to starting assumptions, but the way it grows is based on population and GDP growth. We also calculate a related value called food requirements, based on nutrition standards and not a function of GDP.

Both Population and Gross Domestic Product (GDP) per person are taken as data rather than modeled, in order to allow the user to select scenarios grounded in commonly cited projections. In the model runs shown, Population is taken from the UN Population Division (UNPD 2015). The simulation allows the user to select a scenario between the Low, Medium, and High Variants. GDP per person is based on data and near-term projections from the World Bank (WB 2016) and longer-term growth rates produced for The Guardian by PriceWaterhouseCooper (Guardian 2011). The simulation allows the user to adjust the growth rate of GDP about the projection. Other datasets could be used for specific scenarios.

Demand for two types of food, Crops and Animal Products, are calculated:

$$Demand = Population * Initial\ Demand\ per\ Person * \left(\frac{GDP\ per\ Person}{Initial\ GDP\ per\ Person}\right)^{Sensitivity\ of\ Demand\ to\ GDP}$$

In this simulation, the user forms the feedback between demand and food available. That is, the calculation of demand sets a target at every point in time, and the user has to adjust policies so that the calculated food produced and available meets demand subject to constraints.

b) Land sector

Four categories of land use are considered, consistent with the Food and Agriculture Organization (FAO) data definitions: Cropland, Pasture, Forest, and Other Land. Land is aggregated over the entire country by number of hectares. The increases and decreases in the area dedicated to each use are balanced so that the total land area is conserved. Area may change from any land use to any other (see figure 5). The changes between land uses can be caused by environmental changes (exogenous in this version) or by human causes; area is a stock as shown in figure 6, subscripted by land use. Deliberate changes in land use act to close the gap between area and desired area for each use, subject to the limitations imposed by the total amount of land and the desired areas of other uses. The formulation follows the following logic:

- If all uses have as much or more area than desired, no changes take place
- If only some uses have less area than desired, land changes use from those that have extra area
- If more area is desired than the total available, land changes use to adjust to distribute the area to be in proportion to desired area

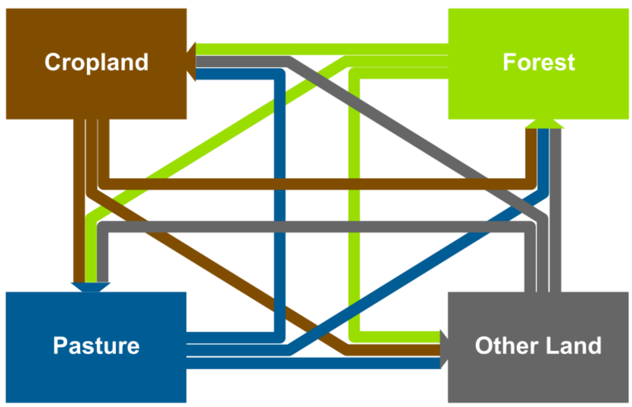

Figure 5: Land Use Flow Schematic

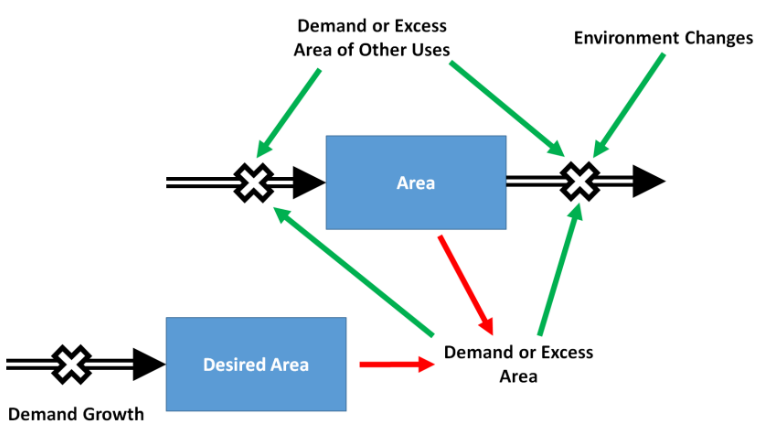

Figure 6: Land Use Area Stock and Flow Diagram

c) Production Sector

In addition to area and desired area, there is a stock of livestock, in Tropical Livestock Units (TLU, a standard measure for normalizing the number of animals by weight). There are also level variables representing the practices relative to production: fertilizer use, and yield for crops and livestock. From these are calculated crops harvested and animal products

$$Crops\ Harvested = Area_{Cropland} * Base\ Crop\ Yield * Yield\ Effect\ of\ Fertilizer$$

$$Yield\ Effect\ of\ Fertilizer = Fertilizer\ Effectiveness * \left(\frac{Fertilizer\ per\ Ha}{Base\ Fertilizer\ per\ Ha}\right)^{Sensitivity\ of\ Yield\ to\ Fertilizer}$$

$$Animal\ Products = Livestock * Livestock\ Yield$$

Additional factors influencing production will be added in future iterations. (for instance? meteological data?...)

d) *Efficiency, Trade Sector, and Food Available*

After food is produced, separate value chain efficiencies are applied to crops and animal products, to represent reduction from post-harvest losses. Food available also depends on imports and exports. Trade is modeled separately for crops and animal products. Exports are modeled as a percentage of production, while imports are modeled as a percentage of demand. Both the percent of demand met by imports and the percent of production exported are level variables. Food available of each type is then:

$$Food\ Available = Harvest * Value\ Chain\ Efficiency + Imports - Exports$$

e) Emission Factors

At this stage in model development, only direct emissions from agriculture (methane and nitrous oxide) are considered. Carbon emissions from land use, land cover changes, and forestry (LULCCF) will be added in future iterations. Emissions are modeled as the total carbon dioxide equivalent (CO_2eq). Only the emission impact of fertilizer is explicit, other factors that affect emission intensity of agriculture are aggregated in the emission factors. Thus:

$$Emissions\ from\ Cropland = Area_{Cropland} * Base\ Crop\ Emission\ Factor * Emission\ Effect\ of\ Fertilizer$$

$$Emission\ Effect\ of\ Fertilizer = \left(\frac{Fertilizer\ per\ Ha}{Base\ Fertilizer\ per\ Ha}\right)^{Sensitivity\ of\ Emission\ to\ Fertilizer}$$

$$Emissions\ from\ Livestock = Livestock * Livestock\ Emission\ Factor$$

The emission factors are themselves level variables, representing the net result of practices, species mix, technology, etc.

f) Policy Characterization

There are seventeen level variables that determine land use, harvest, food available, and emissions. Each has an initial value determined by calibration to data. Some of these have a long term historical trend, some could plausibly have a change in trend, and some could have a discrete response to policy decisions. These are not mutually exclusive. For example, the number of livestock has an historical growth rate; there could be a change in that growth rate; and there could be a specific program which reduces livestock numbers over a specific period. Table 1 lists these seventeen variables and describes the physical meaning, and gives an example of a policy that could change the value.

Table 1: Policy Relevant Level Variables

Variable	Units	Meaning; and Possible Policy
Desired Area [Cropland]	Ha	Land wanted to grow crops; Changing expectations of yield or food demand
Desired Area [Pasture]	Ha	Land dedicated to grazing; Greater use of mixed farming
Desired Area [Forest]	Ha	Forest land protected from conversion; Creating reserves
Desired Area [Other Land]	Ha	Land needed for urban, grassland and other uses; Slowing urban growth
Livestock	TLU	Total animal stock maintained; Shifting dietary preferences
Fertilizer per Hectare	kg/ (yr Ha)	Average application of fertilizers; Subsidizing or taxing use
Input Effectiveness	DMNL	How well fertilizer contributes to yield; Adopting more efficient application methods
Base Crop Yield	kg/ (yr Ha)	Average food productivity of land if fertilizer use held constant; Adopting higher yielding varieties
Livestock Yield	kg/ (yr TLU)	Meat, eggs, milk, etc. produced by a given herd size; Adopting techniques to improve animal health
Percent Crop Harvest Exported	%	Fraction of harvest bound for export; Trade policy
Percent Crop Demand Imported	%	Fraction of domestic consumption met by imports; Changing food preferences
Percent Animal Product Exported	%	Fraction of harvest bound for export; Trade policy
Percent Animal Demand Imported	%	Fraction of domestic consumption met by imports; Changing food preferences
Crop Value Chain Efficiency	%	Fraction of harvest that reaches consumers; Improved transportation networks
Animal Value Chain	%	Fraction of harvest that reaches consumers; Adopting

Efficiency		refrigeration
Base Crop Emission Factor	kg CO_2eq/ (yr Ha)	Average CH_4 & N_2O emissions from farmland if fertilizer use held constant; Adopting no-till or other techniques
Livestock Emission Factor	kg CO_2eq/ (yr TLU)	Average CH_4 & N_2O emissions from a given herd size; Substituting non-ruminants for cattle

As levels, these variables only vary through their change rates. The seventeen associated change rates are calculated at any time as the sum of an applicable baseline value plus the effects of any policy interventions. Baseline values are derived from the calibration process (q.v.), and represent historical and expected trends. The model allows for the possibility that the baseline value may change; if for example a new rate of growth was caused by conditions exogenous to the model boundary. Only one baseline value for each change rate is in use at a given time.

Policy values for these change rates are cumulative. These represent the results of specific changes to the agricultural system, whether as a result of government policy or programs, economic forces, social, or technological changes. Some of these changes might be a permanent alteration of the long term trend, but more likely would be some type of diffusion process. In either case, the policy effect occurs over a characteristic time, which is itself a variable. The total characterization of a policy is given as:

1. Start Time
2. What variable are affected
3. Time constant for taking affect
4. Maximum effect on those variables
5. In which manner the change occurs

The policy structure is subscripted by period and affected variable for a more compact structure. The policy definitions are entered into a spreadsheet table for easy reading (included with the supplementary material), but pasted into Tabbed Array functions in Vensim for simplicity. With the policies defined this way, the user interfaces by selecting which policies are active and how successfully they are implemented, and how rapidly. Other constants that may be subject to policy will be added in future expansions.

3. *Data and Calibration*

The simulations shown and discussed here are calibrated to the Ethiopia case, as mentioned above, because the published documents are useful for the purpose. Plans and policies are taken from Ethiopia's strategic documents (Ethiopia 2011, 2015a, 2016), while historical data are obtained from the FAO (FAOSTAT 2017) or Ethiopia's National Communication to the

UNFCCC (Ethiopia 2015b). Data and projections for Population and GDP per person (WB 2016, Guardian 2011) are not part of the calibration process, but are directly used to calculate demand.

There is a logical order to the calibration sequence. First adjusted are initials and growth rates to match the direct data on land use, livestock, and fertilizer. Second is yield, yield change rates, and sensitivity of yield to fertilizer to match harvest data. Third is import and export fractions and their change rates, and sensitivity of demand to GDP, to match import and export data. Finally, emission factors and sensitivity of emission to fertilizer are adjusted to match emission data.

Tables of initial values for constants, historical policy values, and the data are easiest to read in the spreadsheet included with the supplementary materials. Graphs of model output compared to data in the calibration condition are shown, with reference to the data source, below in Appendix 1.

4. Experiments

The purpose of this modeling project is in part assessing policy options. More work will be needed to do this completely, but we can make initial tests of the strategy put forth by Ethiopia (2015a, 2015b). Ethiopia's plan includes goals for reducing the growth in emissions from livestock compared to business as usual. There is a combined goal for lower emissions from cropland plus CO_2 removal (or negative emissions) from afforestation made possible by reducing land used for agriculture.

Many changes are mentioned in these strategic documents, all intended to be consistent with four "pillars" of the Green Economy Strategy (Ethiopia 2011):

- Improving crop and livestock production practices to increase food yields, hence food security and farmer income, while reducing emissions
- Protecting and re-establishing forests for their economic and ecosystem services, including as carbon stocks
- Expanding electric power generation from renewable sources of energy fivefold over the next five years for markets at home and in neighboring countries
- Leapfrogging to modern and energy-efficient technologies in transport, industry, and buildings.

Specific actions applied to croplands include:

- Increased fertilizer to increase yield
- Optimizing fertilizer to reduce use while increasing yield
- Improved techniques and crop varieties to raise yield
- Tillage and water management to reduce emissions
- Combined crop / livestock / forestry practices to reduce land use

- Using higher production to reduce need for land use

While for livestock, actions include:

- Value chain efficiency, to increase availability without increasing production
- Improved varieties and off-take practice to increase yield
- Feeding and health to increase yield
- Manure management to reduce emissions
- Changing species mix (i.e. chicken instead of cattle) to lower emissions
- Combined crop / livestock / forestry practices to reduce land use
- Using higher production to slow reduce the need for livestock growth

Neither the model at this stage nor the strategy documents have sufficient detail for a detailed assessment. In particular, the scale and timing are not complete enough to scale the policy definitions with precision. We have defined the policies such that the total impact would be approximately equal to the goals stated in Ethiopia's Communication to the UNFCCC (2015). For simplicity, all actions are assumed to start in 2020 and last long enough to reach maximum diffusion. With those caveats, policy options are defined to have the effects listed in Table 2. We are then able to mix the policies and evaluate the impact on key variables.

Table 2: Policy Definitions for Testing

Slower Land Growth	Lowers trend in increasing Desired Cropland and Desired Pasture by up to 5%/year (can make the desired areas actually decrease)
Adopt Higher Fertilizer	Adds up to 50% to fertilizer use, on top of already increasing use trend
Crop Practices	Increases crop yield by (1) Raising the Base Yield up to 20%, and (2) Raising Input Effectiveness by up to 30%
Crop Value Chain	Increases Crop Value Chain Efficiency by up to 50% (lowering postharvest losses)
Tillage and Water Mgt	Lowers Cropland Emission Factor by up to 30%
Slower LS Growth	Lowers trend in Livestock Growth Rate by up to 5%/year (can make the desired areas actually decrease)
LS Practices	Increases Livestock Yield by up to 30%
LS Value Chain	Increases Animal Value Chain Efficiency by up to 50% (lowering postharvest losses)
LS Emission Practices	Lowers Livestock Emission Factor by up to 30%

With these policy definitions, it is possible to achieve Ethiopia's 2030 emission and food goals and maintain food greater than demand through 2050. All successful simulations require substantial success on all or most of the policies; no one element can succeed on its own. Some input / output screens from one such test are shown in figures 7-10 below.

In this scenario, the growth in cropland is halted and livestock numbers decline; fertilizer use is not accelerated but continues its business as usual growth; and high success is achieved in efficiency, technology, and emissions improvements.

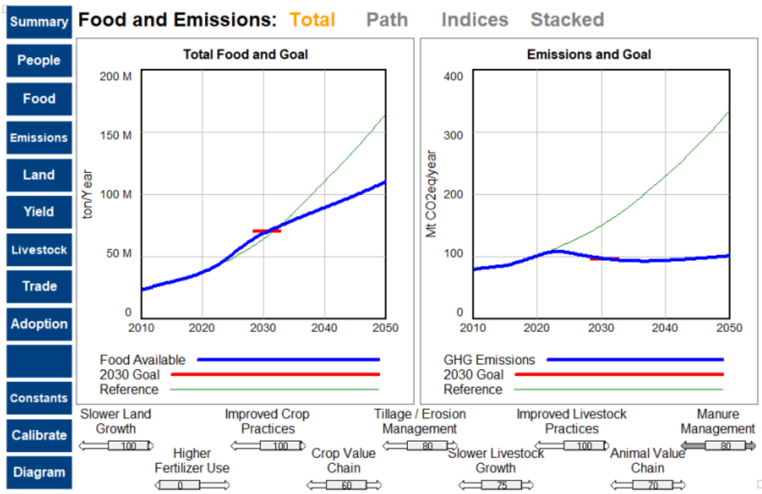

Figure 7: Policy Test Food and Emissions

With this set of policies, Ethiopia meets its food goal in 2030 (figure 7); food available is lower than the reference case but still above demand by 2050 (figure 7 and 8), but the supply of animal products is declining after 2035 (figure 9) and only just meets needs by 2050. If there were no change in diet preferences, livestock would have to increase after that, with consequentially higher emissions.

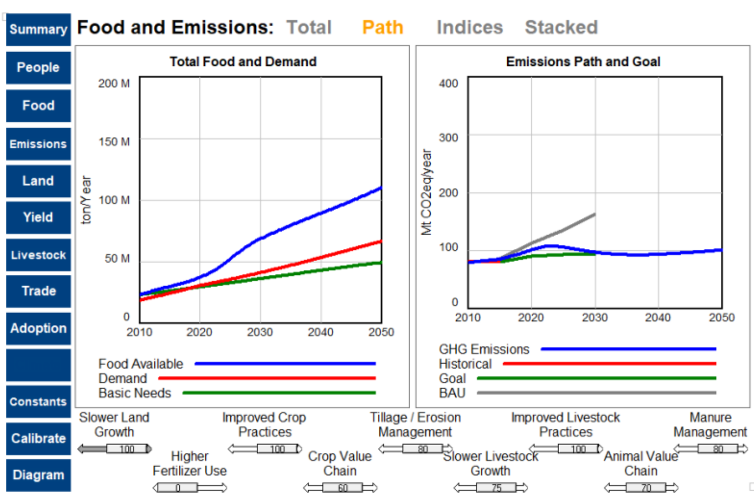

Figure 8: Policy Test Food and Emissions versus Goals

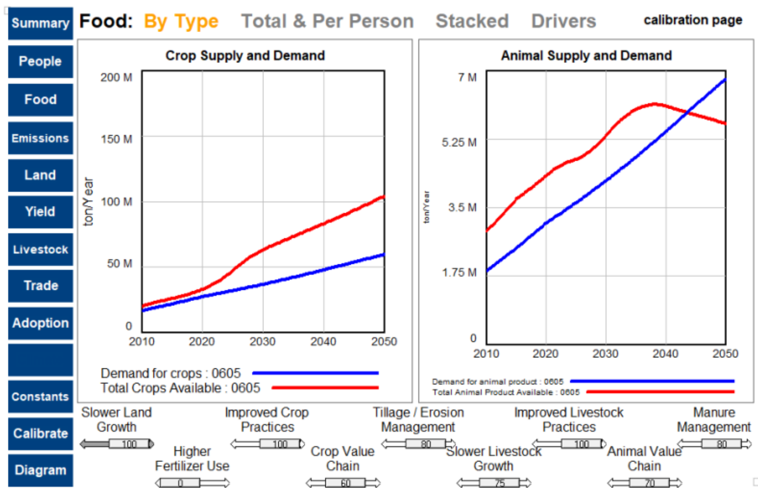

Figure 9: Policy Test Crop and Animal Products

Figure 7 also shows that emissions meets the 2030 goal and are declining at that point. However, they are above the goal pathway until that year (figure 8) before 2040 emissions reach a minimum and begin to increase. They are again above the 2030 goal and rising before 2050.

Although exports are not included as a goal in these strategy documents, and so were not tested in this suite, they do include the general goals of having agriculture support a growing economy. Figure 9 show crops available well exceeding demand, and so it would be possible to add that element and still meet food needs.

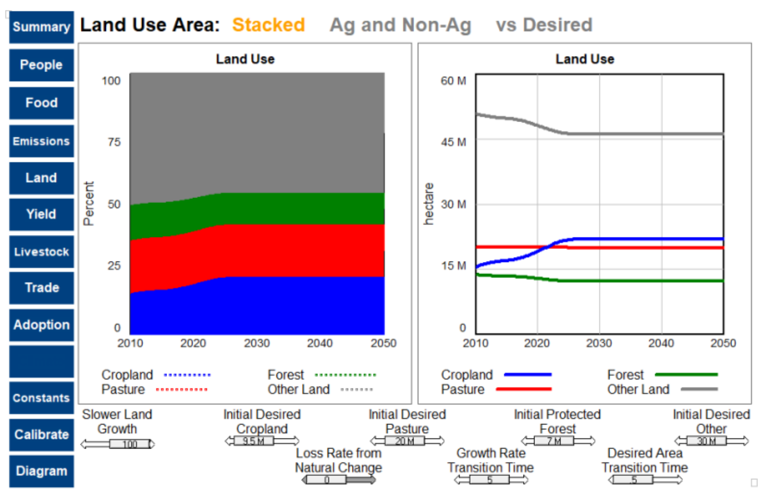

Figure 10: Policy Test Land Use

Figure 10 also shows success on another goal – reducing agricultural land to support reforestation. Deforestation has stopped by 2025 and started to reverse slowly. With the excess food available and lower levels of livestock, there could be land available for reforestation without compromising needs. More detailed land use changes will be added in later expansions to explore this further.

It is clear, however, that even if these policies might be good enough through 2030, in the long term more needs to be done. There is a bound on how low emissions factors can fall and upper bounds on efficiency and yield. If the fundamental driving forces (population, income, and demand) keep rising, emissions can only fall while intensity gains are faster than demand increase. Once efficiencies reach their limits, emissions growth has to increase.

5. Conclusion : Insights, Use and Impact

This project is still underway and further refinements are needed to reach our desired level of detail and robustness. However, even at this stage the tool is useful for conveying insights. The concrete example of Ethiopia's strategy provides some general lessons for Climate Smart Agriculture, or indeed any form of transformation towards sustainable systems. Gains in efficiency, yield, or productivity only make the system more sustainable to the extent that they are used to reduce the drivers of emissions, in this case cropland and livestock. This follows from the observation that to meet emissions goals, both the emissions intensity of activity and the amount of activity have to be controlled. Further, controlling the amount of activity (cropland and livestock) has to address long term trends, not merely, for example, reforesting some specific hectares but letting the baseline growth in cropland continue.

As this project continues we expect to reach two different audiences. First, we hope to be relevant as policy makers make decisions regarding reform of agriculture systems, Nationally Determined Contributions and Mid-Century Strategies, sustainability strategies and the like. Given data and the potential impact of any set of policies, we should be able to analyze the necessary conditions, timing, reach, and combination of policies for success.

Second, we foresee an application in education and outreach. An adaptation of this simulator could be a tool for learning at agricultural, business, or policy schools. In the tradition of Fishbanks or People's Express, a simulation can give a concrete case yet still teach general systemic lessons.

Over the next few months the additional structure we plan to add to the model include: more options for land use changes, to make explicit deliberate reforestation, desertification, urbanization etc.; soil and biomass carbon content, to be able to estimate emissions or absorption from land use changes; interaction between livestock and land available for grazing; and the impact of climate change. We will add measures of resilience and simulate the response to climate-related events, to test the third pillar of Climate-Smart Agriculture. And we will continue to refine as data and estimates of policy impacts become available. Our goal is to work with many African countries in developing a tool suited to each of their needs.

Appendix 1: Calibration Graphs

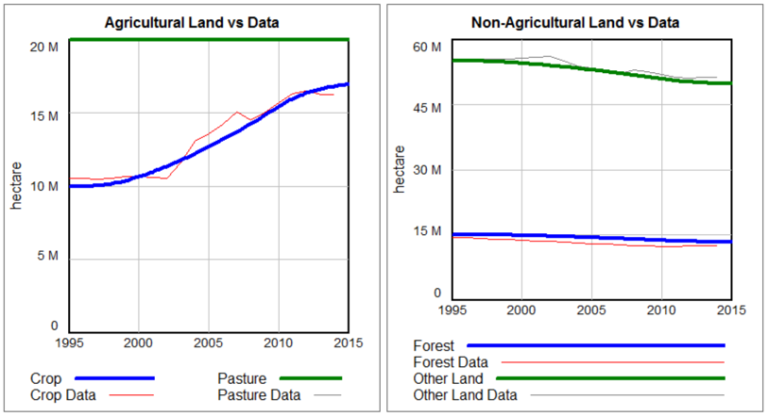

Figure A1: Land sector calibration
Data source FAOSTAT 2017

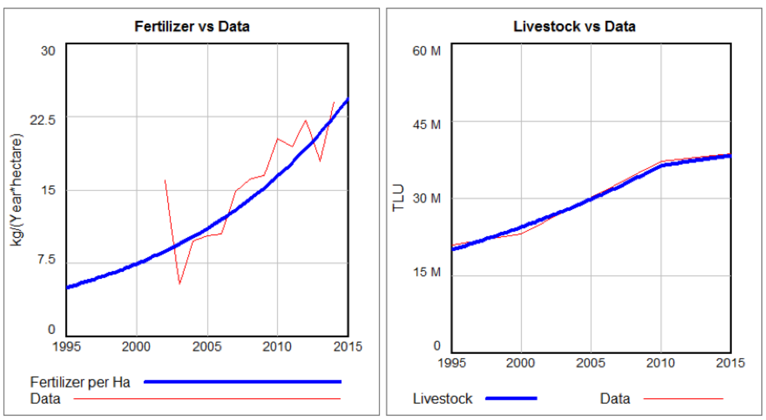

Figure A2: Input (Fertilizer and Livestock) calibration
Data source FAOSTAT 2017

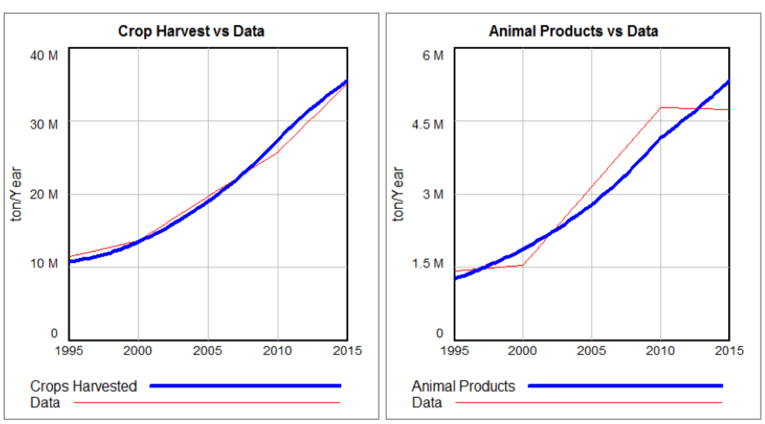

Figure A3: Harvest calibration
Data source FAOSTAT 2017

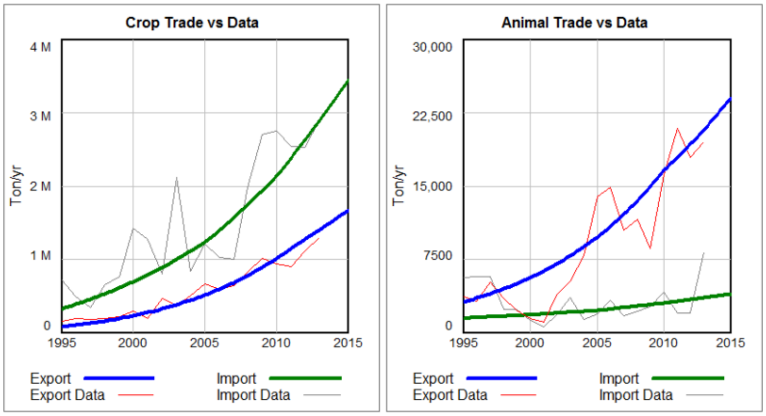

Figure A4: Import and export calibration
Data source FAOSTAT 2017

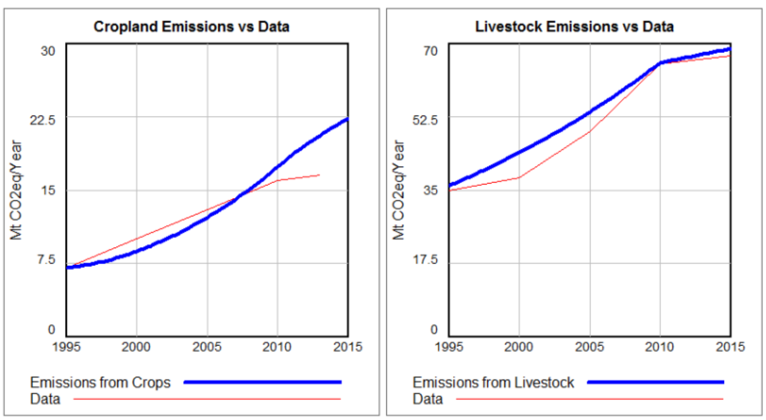

Figure A5: Agriculture GHG Emissions calibration
Data source: Ethiopia 2015b

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