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System Dynamics and Sustainable Intensification of Food Systems: Complementarities and Challenges

Birgit Kopainsky[1], Charles F. Nicholson[2]

[1] System Dynamics Group, Department of Geography, University of Bergen, P.O. Box 7800, 5020 Bergen, Norway; e-mail: birgit.kopainsky@uib.no

[2] The Pennsylvania State University, University Park, PA 16802 USA; e-mail: cfn10@psu.edu

Abstract

Food systems face the challenges of both providing more food for a growing human population and rebuilding and maintaining ecosystem stocks and services. “Sustainable intensification” to achieve these and other objectives has become an important policy goal. Progress towards sustainable intensification can be evaluated against a range of intensification outcomes such as food production, farmer incomes, and nutritional well-being, as well as against a series of sustainability measures. The agricultural literature about sustainable intensification is growing, but our review suggests that relatively few studies have adopted designs and methods required to understand the range of outcomes that would be important for achievement of sustainable intensification. Many analyses of sustainable intensification options suffer from narrow (model) boundaries, limited understanding of how system components interact, and from a short-term perspective that ignores longer-term impacts of sustainable intensification options. Our principal objective is to illustrate how system dynamics concepts and empirical models can help to address each of these limitations. We therefore develop conceptual models to indicate how general classes of sustainable intensification options could be analyzed, and use an empirical system dynamics model of a farm household in Kenya to illustrate the potential for and challenges of sustainable intensification.

Introduction

The conference theme indicates the necessity of "reinventing" systems to address the challenges of a growing human population and the inherent biophysical limits of our planet. This is perhaps nowhere more important than in food systems.

Although the trend in global hunger reduction continues, 805 million people were estimated to be chronically undernourished in 2012–14 (FAO et al., 2014). Global demand for food is increasing and may continue to do so for decades due to an expanding and more demanding (transition to diets with more processed foods and resource intensive animal products) world population. At the same time, agriculture already now has major global environmental impacts (Foley et al., 2005; Millennium Ecosystem Assessment, 2005). About one quarter of global greenhouse gas emissions, for example, result from land clearing, animal husbandry, and fertilization (Burney et al., 2010). Climate change (e.g., Godfray et al., 2011; Schmidhuber & Tubiello, 2007) and the evolution of supply chains in many developing nations (Gómez et al., 2011) pose additional challenges to food systems.

To meet the world's future food needs, food provision must grow substantially while, at the same time, agriculture's environmental impacts must shrink considerably. Food systems thus must become more intensive, but also more sustainable, and sustainable intensification has quickly turned into an important paradigm for the further development of food systems (e.g., Garnett et al., 2013; Godfray et al., 2010; Foley et al., 2011; Tilman et al., 2011).

Food systems, at a minimum, comprise the sets of activities involved in food production; processing and packaging; distribution and retail; and consumption (Ericksen, 2008). A food system includes the determinants and outcomes of its activities. The determinants describe the bio-geophysical as well as the social, economic and political environments that determine how food system activities are performed (food system drivers). These activities lead to a number of social, environmental and food security outcomes. Food system activities and outcomes eventually result in processes that feed back to environmental and socioeconomic drivers (Ericksen, 2008). Food systems are characterized by complex interactions across multiple domains, powerful feedback loops, large time delays, and counterintuitive system behavior (Hammond & Dubé, 2012).

Feedback loops, for example, link food system activities with their environmental as well as their health determinants. Although growing empirical evidence points at the importance of the links and feedbacks between food system activities, the environment and the health system, they have not been extensively modeled (Hammond & Dubé, 2012). Feedback loops are also at the heart of various types of development traps such as natural resource traps, poverty traps, and combinations thereof. A central feature of such traps is the existence of thresholds in assets that define whether a reinforcing feedback loop acts like a vicious or virtuous cycle. Such thresholds characterize e.g. households that are unable to escape from poverty and associated food insecurity (Stephens et al., 2012).

Accumulation is equally central to food systems. Environmental resources needed for food sector activities include but are not limited to stocks of land, water, and nutrients. The condition of these resources affects their productivity and thus the outcome of food system activities. Food system activities involve inventories of food that is produced, food that is processed and distributed, and food that is available for consumption. Managing accumulations is thus relevant not only in natural resource management situations such as soil nutrient management (Saysel, 2014) but also in the operation of value chains (e.g., Sterman, 1989a, 1989b) and in commodity cycles (Arango & Moxnes, 2012).

Given the dynamic complexity inherent in food systems in general and in sustainable intensification specifically, the purpose of this paper is to discuss how system dynamics concepts and models can facilitate the analysis and achievement of sustainable intensification in light of the multiple challenges the concept presents

Literature review

"Sustainable intensification" is a paradigm or policy goal that strives to utilize existing agriculture land to produce greater yields, better nutrition and higher net incomes while reducing reliance on external inputs such as pesticides and synthetic fertilizers and lowering greenhouse gas emissions and other negative environmental impacts. This ought to be done in a way that is equitable and efficient, resilient to future shocks and stresses, and that rebuilds the stock of natural environmental capital as well as the flow of environmental services such as carbon sequestration, flood protection, groundwater recharge and landscape amenity value (Garnett, et al., 2013; The Montpellier Panel, 2013).

The main goal of sustainable intensification is to raise productivity (as distinct from increasing the volume of production) while reducing environmental impacts, that is, raising yields per unit of input (including nutrients, water, energy, capital, and land) as well as per unit of undesirable output (such as greenhouse gas emissions or water pollution) (Garnett & Godfray, 2012). The extent to which overall food production needs to increase in the coming decades depends on progress on improving other food system activities and drivers such as governance, waste, dietary patterns, and population growth (Campbell et al., 2014).

Figure 1 describes a theoretical model of sustainable intensification. It lists the various inputs as well as outputs of the sustainable intensification process and links inputs with outputs through three intensification pathways (The Montpellier Panel, 2013):

- Ecological intensification: Application of agricultural ecological processes such as intercropping, integrated pest management, conservation farming or organic farming.
- Genetic intensification: Use of modern plant and livestock breeding to increase yields, improve nutritive value, create resilience to pests, diseases and climate change.
- Socio-economic intensification: Creation of enabling environments such as markets, building social and human capital.

Figure 1 also provides a range of sustainability measures, that is, criteria for evaluating whether intensification is also sustainable.

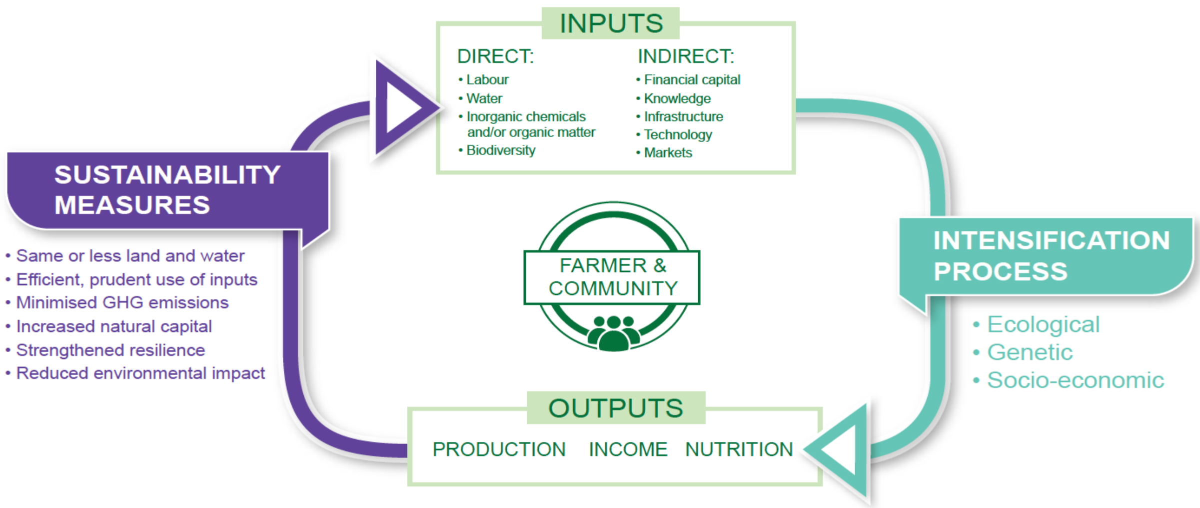

Figure 1: Theoretical model of sustainable intensification (The Montpellier Panel, 2013: 12)

Sustainable intensification denotes an aspiration of what needs to be achieved. The paradigm itself does not privilege any particular agricultural production system over another, which has led both to confusion about and criticism of the concept (Garnett & Godfray, 2012). The merits of different approaches should be rigorously tested and assessed, taking biophysical and social contexts into account. Consequently, implementation of sustainable intensification is context- and location-specific (Garnett, et al., 2013).

Table 1 provides an overview of farming practices and technologies that support the ecological or genetic intensification of agricultural production. The table is based on several review articles such as Foley, et al., 2011; Godfray, et al., 2010; Pretty et al., 2010; Pretty et al., 2011; The Montpellier Panel, 2013; Tilman et al., 2002. The table is limited to agricultural production and thus excludes strategies such as waste reduction or changes in diets. It also does not discuss the creation of enabling environments or the development of social, human or financial capital.

Table 1: Farming practices and technologies for sustainable intensification

Intensification Strategy	Practices and technologies	Outputs	Sustainability measures	Limitations/ comments
Ecological intensification	Intercropping	Higher diversity of produce	Substitution of inorganic fertilizer	Knowledge and labor intensive Difficult to practice at scale May reduce yields?
	Integrated pest management	Higher diversity of produce	Substitution of pesticides	Knowledge and labor intensive Difficult to practice at scale May reduce yields?
	Conservation agriculture	Higher yields in water scarce seasons	Prevention of soil erosion Improvement of soil fertility Accumulation of soil organic carbon	Knowledge and labor intensive
	Organic farming	Lower yields when practiced at scale	Wide range of sustainability improvements	Knowledge and labor intensive
Genetic intensification	Higher yields	Improved yields	Depend on requirements for complementary inputs	Capital intensive Unclear accessibility and affordability Unclear long-term effects (e.g. resistance)
	Higher nutritive values	Improved nutrition		
	Resistance to pests and diseases	Resilient yields		
	Resistance to climatic variability	Resilient yields		
	Nitrogen uptake and fixation		Lower requirements of inorganic fertilizer	

The review articles summarized in Table 1 mainly document the impact of a series of individually-implemented farming practices and technologies on selected sustainable intensification outcomes. However, these reviews do not entirely fit with the comprehensive definition of sustainable intensification, because they fail to consider all (or at least several) production, income and nutrition outcomes as well as all sustainability criteria simultaneously. For example, crop yields may have been increased, but there was no reporting of environmental effects such as leaching of nitrogen and phosphorous into ground or surface water from the same study. This implies that relatively few studies have adopted the design required to understand the range of outcomes that would be important for demonstrating achievement of sustainable intensification.

Dynamic complexity of sustainable intensification

Figure 2 interprets the sustainable intensification literature from a system dynamics perspective at a highly aggregated level. The processes displayed in Figure 2 are inspired from Gerber, 2015, Stave & Kopainsky, 2015), and Stephens, et al., 2012) and the literature quoted therein. Processes are generic as much as possible but mainly represent selected aspects of a developing country context with mixed crop-livestock farming systems and high prevalence of food insecurity.

In line with the theoretical model for sustainable intensification (Figure 1), the diagram in Figure 2 differentiates between inputs to and outputs from a sustainable intensification process as well as sustainability measures. Water and nutrients, both stocks, represent inputs to the sustainable intensification process (variables in bold and italics). Animal production and crop production are indicators to measure production outcomes while consumption shortfall represents a nutrition outcome. Income outcomes are directly represented by the stock of household cash assets (variables with a dark grey background), and in keeping with the economic model of the household (Singh et al., 1986) models consumption in value terms based on total accumulated cash values of production. Finally, variables with a light grey background indicate sustainability measures. The land and water stocks keep track of whether the sustainable intensification process complies with the requirement of using less land and water for generating the same outcomes. Inorganic fertilizer is an example of a non-renewable input that needs to be used efficiently and prudently. Greenhouse gas emissions resulting from animal husbandry and deforestation as well as nutrient losses provide information on the environmental impact of the sustainable intensification process. The stock of soil organic matter provides one example of natural capital that needs to be increased.

Figure 2 describes an example of a reinforcing and a balancing loop. It is selective in that it does not represent the full range of feedback loops responsible for the development of intensification outcomes and sustainability measures over time. For example, the figure does not include content about economic components, particularly price dynamics. For more detail about how crop and animal production would be valued, cf. for example Stephens, et al., 2012).

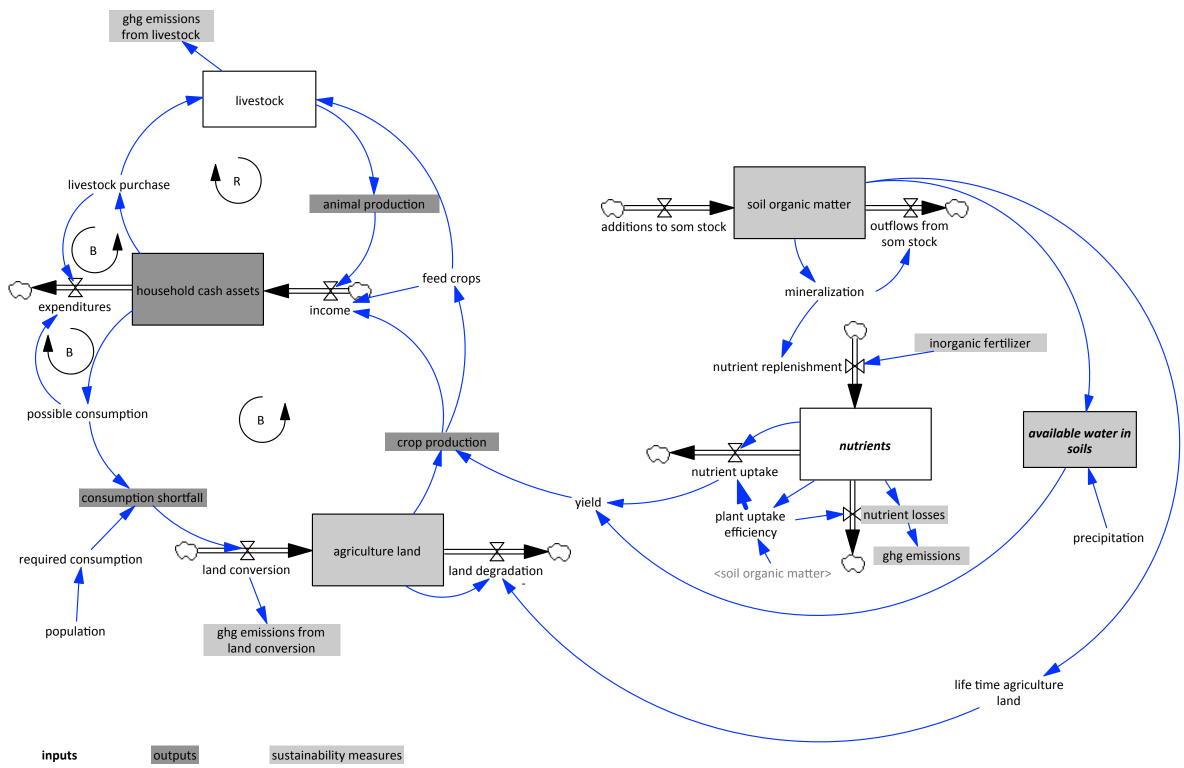

Figure 2: Representation of sustainable intensification principles in system dynamics terms

Figure 3 provides a refined representation of sustainable intensification. Compared to Figure 2, it adds structures for ecological as well as genetic intensification based on the sustainable intensification practices and technologies listed in Table 1 (structures highlighted with bold arrows). Ecological intensification pathways are described by the links from ‚livestock' to ‚manure from livestock' to ‚manure application to land', which adds to the ‚soil organic matter' stock. Soil organic matter is also built through the application of crop residues (stemming from crop production) to land. A third ecological intensification pathway originates from the use of nitrogen fixing crops in ‚crop production' that add to the stock of nutrients in topsoils.

Genetic intensification in Figure 3 originates either from a stock of genetic potential that defines the production limit of crops. Genetic intensification could also strengthen the link between livestock and animal production by increasing the productivity of livestock. Additional entry points for genetic intensification are improvements in plant uptake efficiency or in the efficiency of water use, represented in the link between available water and yield.

With the addition of the intensification pathways, Figure 3 describes a series of reinforcing ecological feedback loops (where crop production feeds the accumulation of ecological resources such as soil organic matter and nutrients, which in turn increase crop production) and also a reinforcing socio-economic loop (where the accumulation of livestock increases household income, which, in part, can be re-invested in livestock and continue adding to this stock or other technologies or resources that promote sustainability). A balancing feedback loop regulates the need for additional agriculture land depending on the gap between required and possible consumption.

For the analysis of the potentials and limitations of sustainable intensification, the feedback loops in Figure 3 have a number of implications. The different ecological feedback loops are reinforcing in nature, however, they have to respect mass balance. Increasing production can lead to increased accumulation of soil organic matter (through the application of crop residues) and nutrients in topsoil (through the cultivation of nitrogen fixing legumes), which in turn increases production. However, the maximum of nutrients that can be returned to the soil through these processes cannot exceed the amount of nutrients that were taken up by crops during plant growth. Thus, although there are a number of reinforcing feedback loops, they do not generate unlimited exponential growth.

The reinforcing feedback loop between livestock, ecological resources and production helps rebuild soil organic matter and provides a renewable source of nutrients. Animal production also improves nutrition outcomes and household income. On the other hand, however, livestock is an important contributor to greenhouse gas emissions. The beneficial impacts on some sustainability measures and sustainable intensification outcomes can be accompanied by some serious negative environmental impacts.

Genetic intensification pathways, on the other hand, are likely to have fewer negative impacts from the processes displayed in Figure 3. If a genetic improvement in crops results in greater nutrient uptake, this could reduce/deplete the soil nutrient stock more rapidly. Genetic intensification, however, raises a number of questions regarding equity (are the technologies available and accessible to all farmers?), resilience (dependency on external input supplies; limited agrobiodiversity and diversity of farm management practices) and impacts on other sustainable intensification outcomes that cannot be answered from an analysis of the feedback loops in Figure 3. Some of these issues are mentioned in the limitations/comments column in Table 1.

In conclusion, a conceptual analysis of sustainable intensification from a system dynamics perspective highlights the difficulty of developing and implementing farming practices and technologies to comply with all dimensions of sustainable intensification and to create synergies between outcomes instead of generating undesired outcomes over time.

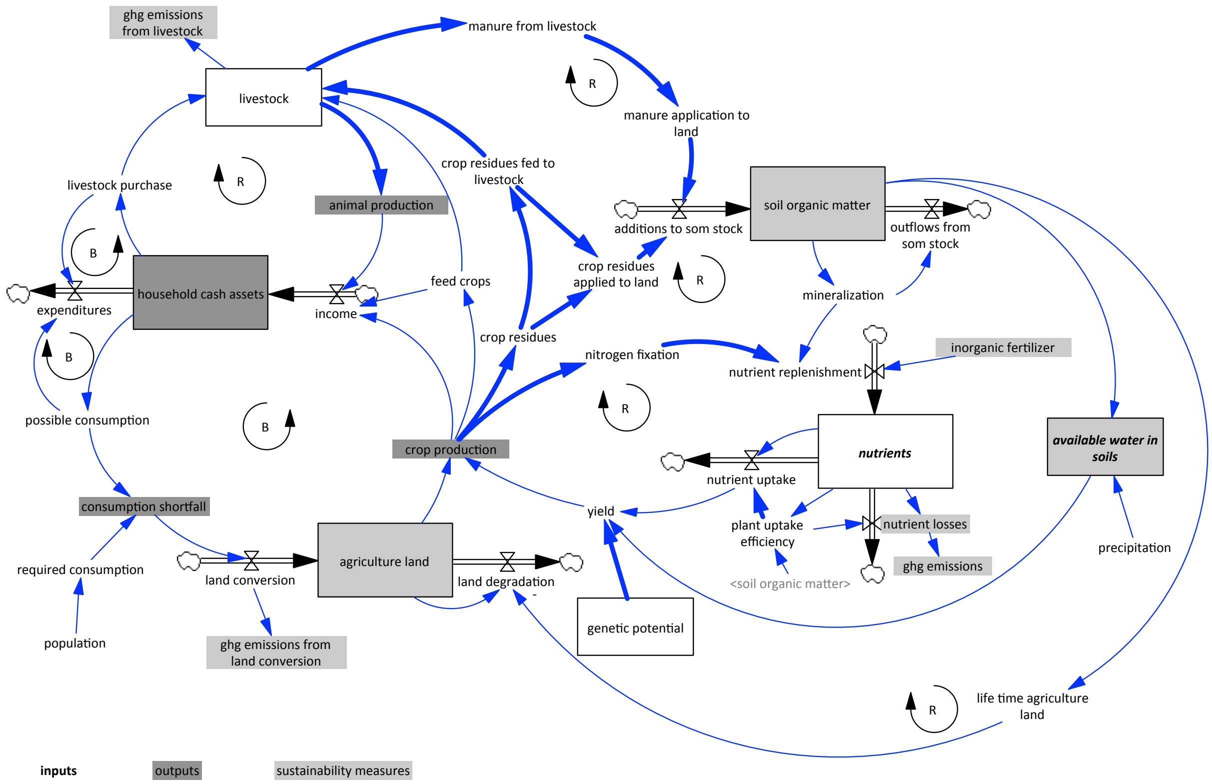

Figure 3: Refined representation of sustainable intensification principles in system dynamics terms (newly added or strengthened structures highlighted with bold arrows)

Figure 3 shows only a selection of processes responsible for crop and animal production and their environmental impacts. Nevertheless, the number of feedback loops and accumulation processes illustrated in the figure are evidence of the dynamic and complex nature of sustainable intensification. A growing number of studies thus emphasize the need for a systems perspective and for the integration of inputs from many disciplines and stakeholder perspectives (e.g., Hammond & Dubé, 2012; Liu et al., 2015; Tedeschi et al., 2011 ; van Ginkel et al., 2013).

As a consequence, systems modeling studies have become more frequent in the agricultural sciences (e.g., Nicholson, 2007; Parsons, Nicholson, Blake, Ketterings, Ramírez-Aviles, Cherney, et al., 2011; McRoberts et al., 2013; Whitman et al., 2011). Social-ecological systems modeling, for example, is an emerging field that formalizes the multiple relationships in social-ecological systems (SES), of which food systems are a prominent example. Although SES research is primarily problem-oriented, the majority of existing SES models is largely theoretical (Schlüter et al., 2012). Agent-based SES models mostly address theoretical issues by providing conceptual models rather than solutions to empirically measurable issues (Janssen & Ostrom, 2006). An additional salient research need in the field of SES modeling is to more explicitly model feedbacks between the social and ecological systems (Schlüter, et al., 2012).

Another important feature of existing systems modeling studies is that they often lack sufficiently broad model boundaries for assessments of sustainable intensification. For example, many crop-growth simulation models have been applied to assess the impacts of management changes and external factors such as climate change (e.g., Turner & Rao, 2013; Webber, 2014) but the model boundaries are often quite narrowly focused on an individual field or plot.

In the next section, we use an existing system dynamics model to studying sustainable intensification in a specific food system. This is a problem-oriented application that includes selected indicators from the entire range of production, income and nutrition outcomes and that allows evaluating synergies and trade-offs created by different sustainable intensification strategies.

Case study system dynamics model

To illustrate the usefulness of SD modeling for assessments of sustainable intensification concepts and the challenges involved in achieving it, we apply the previously-developed Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model (Stephens, et al., 2012). CLASSES contains some but not all of the pathways depicted in Figures 2 and 3, but serves as a useful means of illustrating empirical modeling of sustainable intensification processes and highlighting key challenges. CLASSES describes conditions for a typical smallholder farm household in highland Kenya. These households follow a mixed livelihood strategy, growing some combination of annual food crops, perennial cash crops and perennial fodder crops, maintaining small livestock herds, engaging in either unskilled or – if the household has adequate educational attainment – skilled wage labor, and receiving income transfers (often from family members residing elsewhere). Although smallholder farming systems are diverse, we represent each of these elements of the livelihood strategy with the dominant activity observed in highland Kenya (Brown et al., 2006). Maize represents the dominant annual food crop in the region, Napier grass represents the primary fodder crop, tea represents a common perennial cash crop, and livestock are represented by crossbred dairy cattle. Wage labor is represented by opportunities for skilled and unskilled off-farm employment, and income transfers are represented by remittance payments.

Model structure

The model has three primary modules that interact with each other over the course of 100 quarters (25 years). A crop and soil module describes the different cropping choices (how much land to be allocated to maize, Napier grass and tea each quarter) and subsequent yield and soil nutrient dynamics on the farm (in terms of soil organic matter, soil nitrogen and phosphorus stocks). A livestock module describes the livestock herd dynamics, tracking the number, physiological state and productivity of individual dairy cattle and their feed requirements. An economic module links farmer decision making on resource (land, labor and fertilizer) allocation to these activities each quarter and to the observed outcomes from each of the above activities, which can be complemented by off-farm skilled and unskilled employment opportunities. Stephens, et al., 2012 describe CLASSES in more detail and discuss its application to household-level food security indicators.

Several important reinforcing feedback processes link the crop and livestock modules, which determine dynamic behavior (Figure 4). One important reinforcing process (indicated by red arrows) is that larger maize crop harvests lead to greater cash accumulation (through increased maize grain values), which facilitates the acquisition of livestock assets (and more crop residues to feed them). More livestock also results in more milk production, which increases household cash available (in addition to food availability). The crop and soils module plus the livestock module comprise the model's biophysical system.

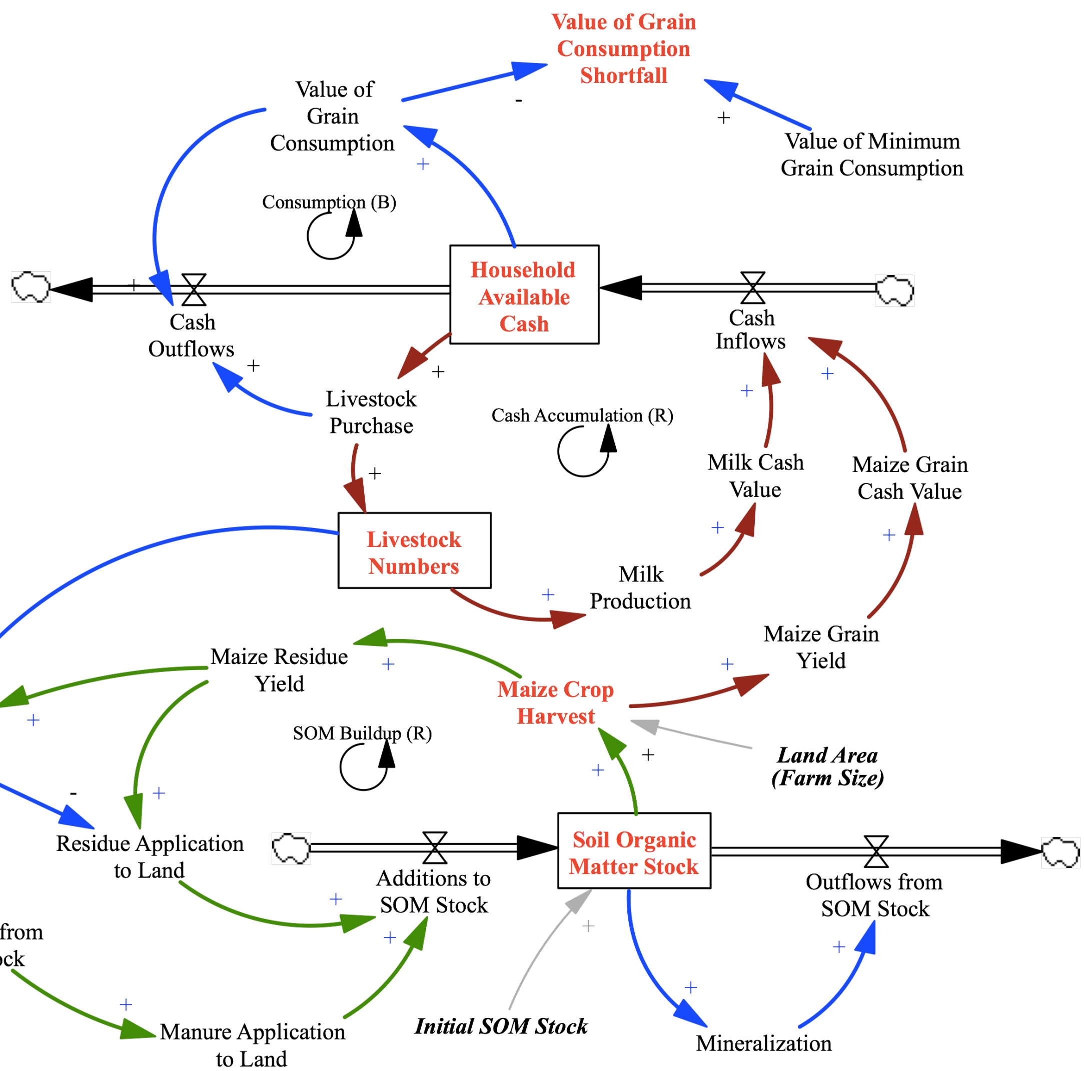

Figure 4: Overview of Principal CLASSES Model Structure Stocks and Feedback Loops

Scenarios and variables

To illustrate the application of CLASSES to sustainable intensification, we examine three scenarios and the dynamic behavior of five variables. The *Baseline* scenario assumes the household with 0.35 ha of arable land divided into 10 plots produces only a maize crop twice each year (during the long rainy season and the short rainy season) for 25 years without the use of inorganic fertilizers. This is rather typical of the sites in Kenya for which the model was developed, although we choose a farm size smaller than the average to illustrate a resource-poor household that is often the target for sustainable intensification efforts. One intensification scenario, *Maize Fertilizer*, assumes continuous cropping of maize twice each year, but with fertilization based on recommended application of 123 kg/ha diammonium phosphate (DAP, which contains both nitrogen and phosphorus to support maize plant growth) on all 10 maize plots beginning at quarter 20. Although this is a simplistic scenario in terms of management practices, it is one potential means of system intensification, in terms of increasing yields per unit land area (even if it ignores potential environmental impacts involved in the production and transportation of the fertilizer). It is consistent with the Montpellier Panel (2013) recommendation for “more effective inputs of water and nutrients…” . A second intensification scenario, *Maize Napier Heifer*, assumes that households will crop both maize and Napier grass on 5 of 10 plots (total area 0.175 ha for each crop), and will begin the simulation with one bred heifer that will give birth to a calf and produce milk. The integration of crops and livestock has long been viewed as a means of intensifying cropping systems (McIntire et al., 1992) and in many regions this process continues to play an important role in the evolution of agricultural systems. The Montpellier Panel (2013) noted that “exploiting synergies between crops and livestock” is one approach to achieve intensification.

We evaluate the impact of the two intensification scenarios on five variables that represent the three different components of SI discussed in the Montpellier Panel (2013) framework. Maize production per harvest per farm represents the “Production” component of the framework, cash and livestock assets of the household represents the “Income” component, and the amount of money required to purchase maize grain to cover any shortfall of own maize production compared to household minimum consumption needs represents the “Nutrition” component of the framework. We also examine two variables that are related to production and environmental effects: total soil organic matter (SOM) and losses of nitrogen (N) to the environment outside the farm. SOM has a number of beneficial effects in cropping systems (Victoria, 2012) and N emissions from the farm tend to have negative environmental effects (such as eutrophication of waterways and greenhouse gas emissions). All simulations are run for 100 quarters (25 years) in Vensim Pro® using Euler integration with a time step of 0.015625 quarters.

Simulation results

The *Maize Fertilizer* strategy is effective at increasing total maize production relative to the *Baseline* over 25 years (Figure 5), increasing average maize yields and total production by 29%. However, yields show a decreasing trend after about quarter 40, indicating the level of fertilization would need to increase over time to support sustained yields. Maize production is actually nearly 20% lower with livestock on the farm, despite yields per unit land area that are highest of three scenarios (increasing by more than 60% compared to the *Baseline*) because half of the farm's land is now allocated to growing forage rather than the food crop. However, maize production with livestock also does not decline over time, due to N and P accumulation in the soil.

However, none of the three strategies is sufficient to prevent declines in SOM (Figure 6). Fertilization slows the rate of SOM decrease, and livestock more so, but continuing decreases in SOM could present an issue at some time in the future, which is inconsistent with the strictest definition of sustainability (over an indefinite or infinite time horizon). In addition, N outflows from the farm increase with both intensification scenarios (Figure 7) and by a large amount when livestock are present. The latter is primarily due to leaching of N in the form of nitrates because the amount of manure applied is large relative to the land area. (Leaching could be reduced through lower application of manure without a reduction in maize yields, although we do not explore that management alternative in detail here.) Gaseous losses of N in the form of the greenhouse gas nitrous oxide also occur from manure in storage when livestock are present. Thus, although the intensification scenarios examined increase yields, they are not completely consistent with a sustainable system without potential for significant environmental impacts.

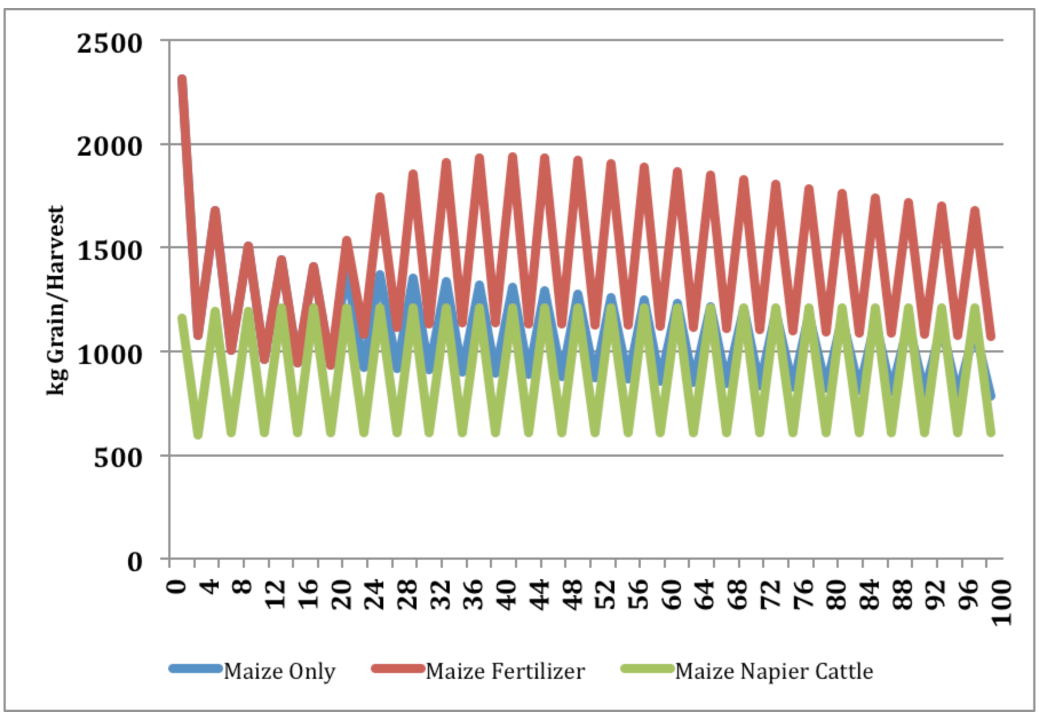

Figure 5: Simulated Maize Production Per Farm, Maize Only and Two Intensification Strategies

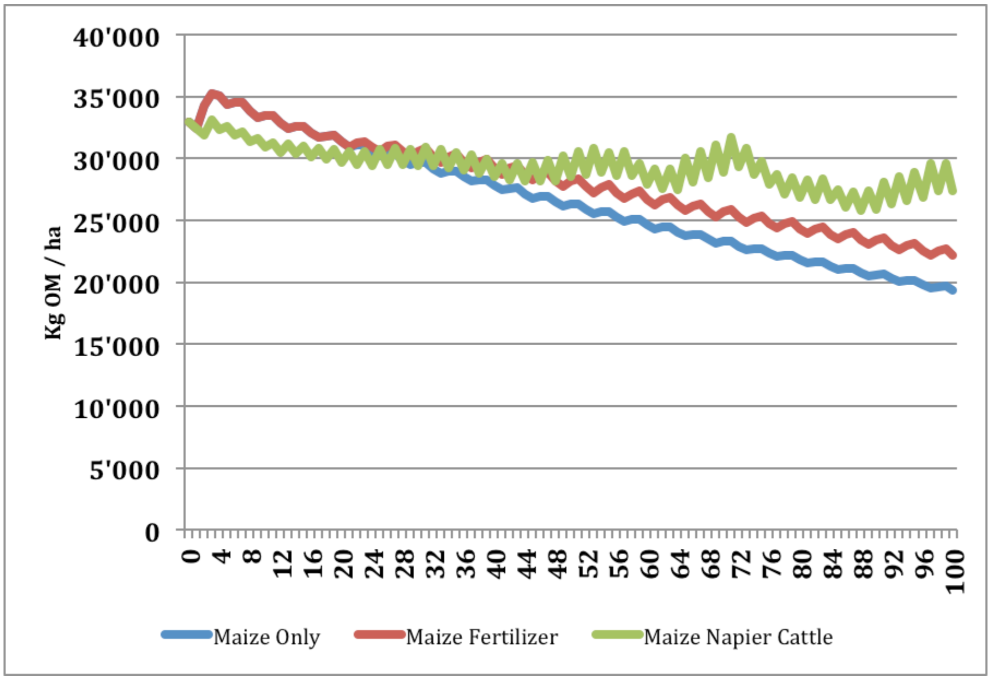

Figure 6: Simulated Total Soil Organic Matter, Maize Only and Two Intensification Strategies

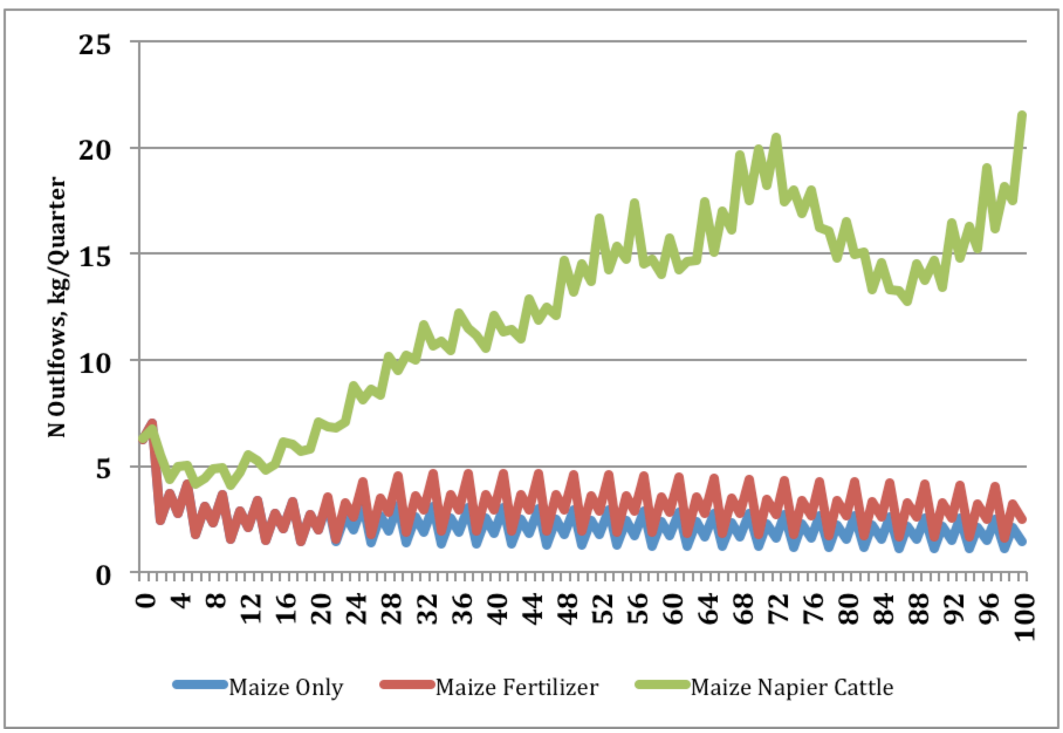

Figure 7: Simulated Nitrogen Outflows from Farm, Maize Only and Two Intensification Strategies

Livestock and cash assets are increased by both intensification strategies (Figure 8 and Figure 9), which suggests that intensification is achieving the objective of increased "income" (given that assets represent the accumulation of income over expenditures). The increase in average cash assets is about 40% with fertilization compared to the *Baseline*, and although crop yields are increased the household also incurs expenses for fertilizer. Livestock and cash assets are nearly ten times higher with intensification through the incorporation of livestock, but the variation is also much larger. This variation arises primarily due to variation in milk sales, which occur only for mature female animals during the lactation period (there are numerous periods where no milk is available for sale and the household incurs other expenses for maintenance of the livestock herd). This high degree of variability and occasional period when cash assets with livestock are below those for the scenarios where only maize is cropped may be a significant concern to farm households and policymakers.

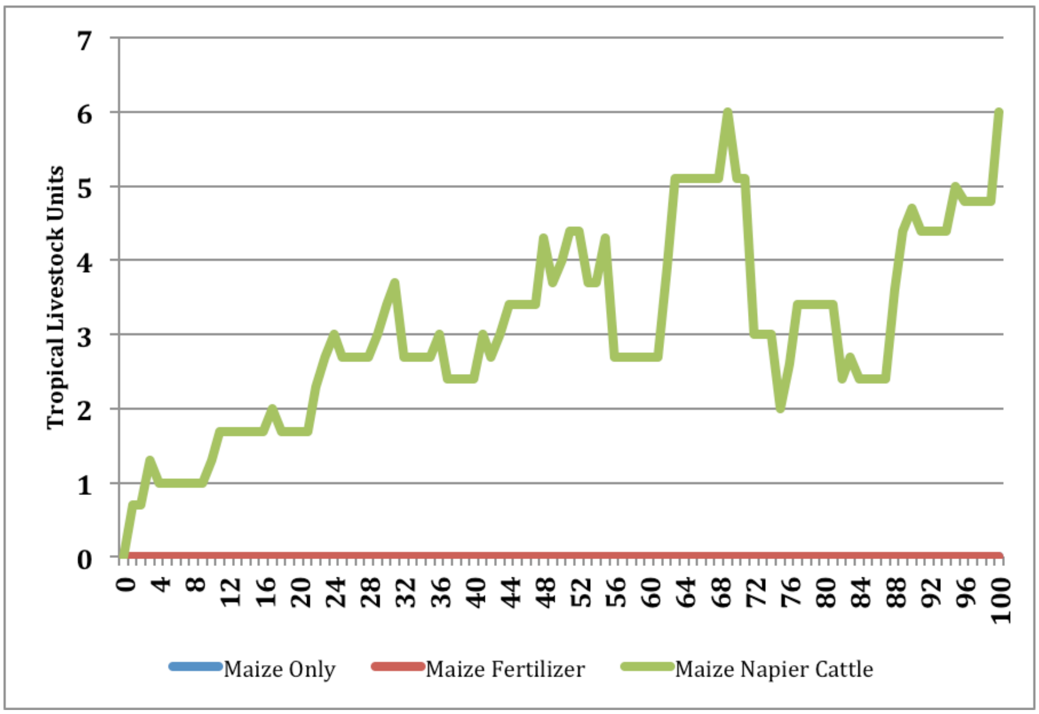

Figure 8: Simulated Tropical Livestock Units Owned by the Household, Maize Only and Two Intensification Strategies (Note: Neither the "maize only and "maize fertilizer" scenarios include livestock, so the blue line and red line overlap in the figure.)

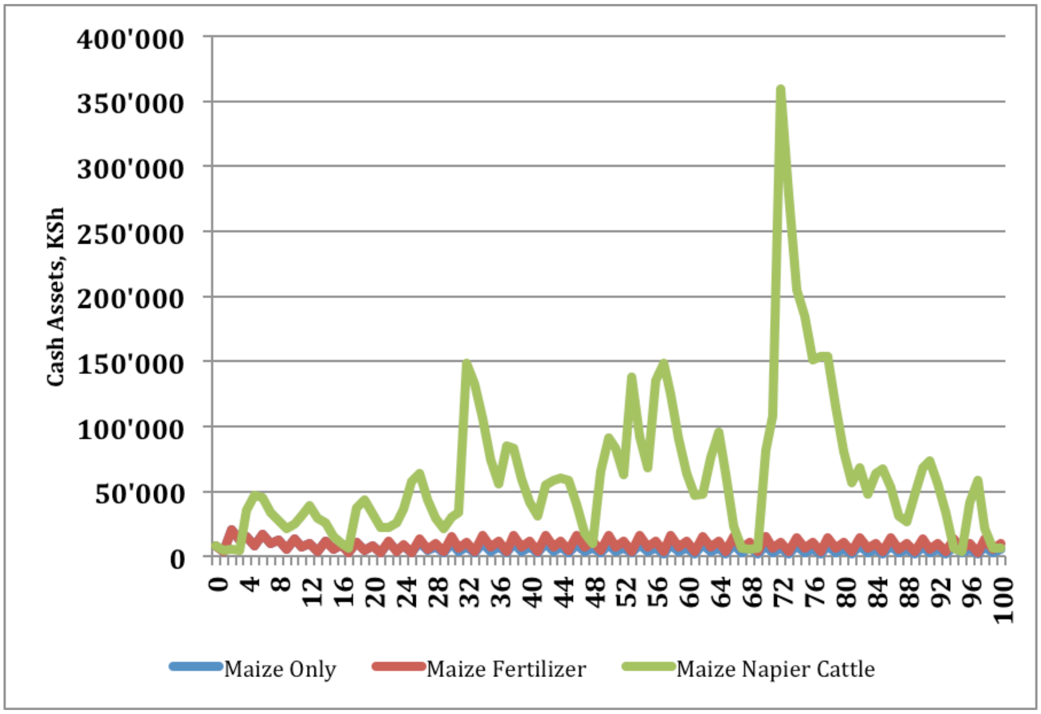

Figure 9: Simulated Cash Assets, Maize Only and Two Intensification Strategies

Food insecurity (indicated here as the value of the shortfall of own maize production compared to minimum household consumption requirements) occurs in part of every year other than right after maize harvest beginning in year 4 (quarter 20) for the Baseline scenario (Figure 10). Given the land available for planting to maize and yields, households cannot produce sufficient maize to meet their minimum consumption requirements once soil nutrients decline to a threshold level. These shortfalls initially occur only after the grain from the maize crop planted for the short rains is exhausted, but as the soil nutrients are depleted over time (Figure 7) and yields decrease (Figure 5), the shortfalls become more frequent and their values larger. Fertilizer use changes this pattern so that the shortfalls are made smaller and then disappear after quarter 32, but then return in a persistent manner after quarter 64. Incorporating livestock into the system reduces the frequency and extent of shortfalls, but does not eliminate them. These results suggest that neither intensification strategy will completely and permanently eliminate consumption shortfalls—even if they make marked improvements compared to less intensive management practices.

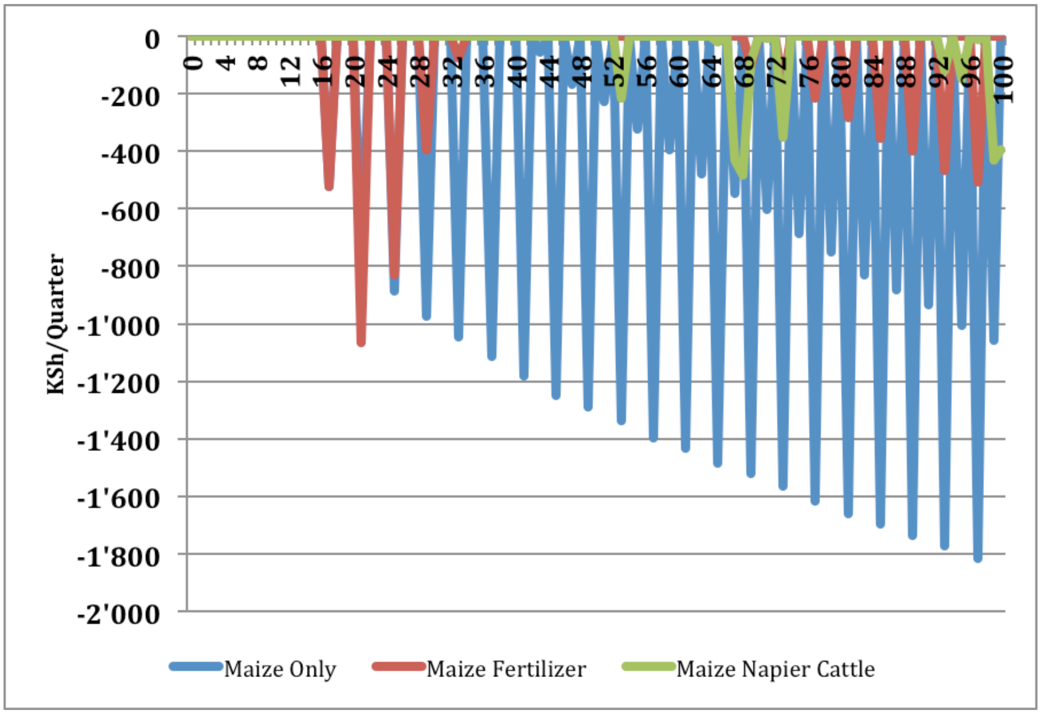

Figure 10: Simulated Value of Staple Food Consumption Shortfall, Maize Only and Two Intensification Strategies

Discussion and conclusions

The purpose of this paper was to discuss how system dynamics concepts and models can facilitate the analysis and achievement of sustainable intensification. For this purposed, we reviewed the sustainable intensification literature, identified the dynamic complexity involved in the design and evaluation of sustainable intensification interventions, and presented a case study system dynamics model that illustrates some of the issues arising from an integrated, systems-oriented analysis of a concrete food system.

While our case study system dynamics model allowed evaluating changes in all categories of important outcomes (production, income, and nutrition) and against a series of sustainability measures, it was limited to the analysis of selected ecological intensification pathways. Further developments of the model would have to include additional ecological and especially genetic as well as socio-economic intensification pathways.

Another limitation of the CLASSES model in the context of sustainable intensification is its fairly narrow geographical focus. Often, success can be achieved on a small scale such as a plot, farm or community. The challenge, however, lies in scaling up success to a regional or national food system (The Montpellier Panel, 2013). The contribution of system dynamics to sustainable intensification studies is in the integrated analysis of direct and indirect, short- and long-term consequences of sustainable intensification practices and technologies. However, system dynamics is less suitable for an analysis of emerging behavior across geographical levels (Kopainsky et al., 2015).

Despite the limitations of our case study, the simulation runs performed with the CLASSES model generated a number of important insights. From the perspective of a system dynamicist, the results for the key indicators are perhaps unsurprising, given that they embody commonly understood principles such as policy resistance, unintended consequences and dynamic complexity. However, these principles are NOT commonly understood or appreciated in much of the agricultural literature and(or) development practice, and therein lies much of the yet-to-be developed complementarity of SD and sustainable intensification. Although alternative scenarios could be developed that would likely demonstrate these outcomes to a lesser degree, these would seem likely to occur in some form for most intensification processes. However, many of the proponents of sustainable intensification appear at best to not fully appreciate these possibilities, the need for and feasibility of simulation modeling to provide relevant insights, or to have at their disposal empirical tools such as CLASSES that could assist in understanding trade-offs and formulating higher-leverage intensification interventions. Thus, the current assessment of sustainable intensification options often seems to suffer from narrow (model) boundaries (consideration of only one set of outcomes rather than a broader range), limited understanding of how system components interact, from the inability to infer dynamics based on conceptual systems models (even if these latter implicitly recognize the importance of feedback loop processes), and from a short-term perspective that prevents studying the long-term impacts of sustainable intensification practices and technologies. Our empirical example thus illustrates how the development and analysis of system dynamics models can help to address each of these limitations. Regarding the last aspect, for example, our case study showed that initial improvements in intensification and sustainability could not be sustained over time.

Given the importance of sustainable intensification and the challenges to accomplishing it, we suggest that there are four main ways in which system dynamics can be applied to assess the limits of sustainable intensification, understand potential trade-offs and to facilitate the greatest degree of sustainable intensification possible. In line with (Stave, 2015), these four ways are:

- Research: Develop models to explain observed behavior, build theory and identify areas for further research. Example system dynamics models in food systems research are: Stave & Kopainsky, 2015; Nicholson & Blake, 2004; Tedeschi, et al., 2011.
- Management/decision making: Develop models to identify and clarify the impact of policy and management actions to change the system's behavior. Example system dynamics models in food systems research are: Kopainsky, et al., 2015; Kopainsky et al., 2012; Lellis Vieira et al., 2011; Nicholson et al., 2011; Parsons, Nicholson, Blake, Ketterings, Ramírez-Aviles, Fox, et al., 2011; Parsons, et al., 2011; Whitman, et al., 2011.
- Stakeholder engagement: Use system dynamics tools and techniques to increase shared understanding (instead of simply eliciting knowledge from stakeholders) as well as identify and clarify impact of policy and management actions. Example system dynamics

applications in food systems research: Hovmand et al., 2010; Yadama et al., 2010; Hager et al., 2015; McRoberts, et al., 2013; Schmitt Olabisi, 2010.

- Learning: Use system dynamics models to communicate key lessons about dynamic complexity. Example system dynamics models in food systems research: Saysel, 2014; food system examples in the Systems Literacy Project (http://www.pbslearningmedia.org/collection/systemsliteracy/).

It is important to emphasize that the complexity and diversity of food systems around the world and the range of uncertainty they face are such that there are no universal practices and technologies for sustainable intensification (Janssen & Anderies, 2013; Ostrom et al., 2007; Ostrom, 2009). Our explanations here focused on a discussion of relevant insights that arise from a feedback perspective on sustainable intensification rather than on the identification of case-specific policy and management actions.

When designing case-specific sustainable intensification actions, situations will inevitably arise where there are trade-offs between the different outcome categories and between outcomes and sustainability measures. In some cases, trade-offs might be minimized through changes to governance systems. However, in many cases, this will not be possible and stakeholders will need to make difficult decisions, ideally based on an informed scientific and socio-economic evidence base, and taking into account long-term resilience as well as short-term costs and benefits (Garnett & Godfray, 2012). It is in this context that system dynamics models can make a powerful contribution, particularly initial higher-level research models that can be used to test to which extent the full range of sustainable intensification options are achievable. Such models also allow identifying the most important research needs and designing experiments and studies that fill these needs.

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