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Full title

Food provision and environmental goals in the Swiss agri-food system: System dynamics and the social-ecological systems framework

Short title

Food provision and environmental goals in the Swiss agri-food system

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Abstract

An important challenge for the Swiss agri-food system is how to align food provision with environmental goals in the context of increasingly complex conditions. This paper describes a system dynamics model that analyses the trade-offs and synergies between these goals arising from different fields of action. The model is grounded in the social-ecological systems framework and was developed in a participatory process with stakeholders across the Swiss agri-food system. Model analysis indicates that yield improvements and the implementation of more sustainable production systems have important leverage for increasing food provision and simultaneously improving environmental performance. However, these fields of action need to be complemented by fields of action outside agriculture such as reductions in food waste and losses or changes in consumption patterns. Model analysis also shows that the feedback perspective, inherent to the system dynamics methodology, promises to yield valuable synergies with the social-ecological systems approach.

Keywords

Food system, system dynamics, social-ecological systems, food provision, environmental welfare

Introduction

Nutrition accounts for approximately one third of the total environmental impact caused by Swiss final consumption (Jungbluth 2011). As Switzerland's footprint is more than four times larger than its biocapacity (BfS, 2014), nutrition is a priority field of action for improving environmental sustainability. Aligning such environmental goals with food provision, however, constitutes an important challenge for the Swiss agriculture and food system (agri-food system). Agricultural support in Switzerland is one of the highest worldwide (OECD, 2009). Nevertheless, domestic food production has been stagnating since the late 1990s and although agricultural policy shifted from production price support to decoupled and ecological direct payments as of the early 1990s, environmental goals are insufficiently achieved (Lanz et al., 2010). In addition, the multiple social, economic and environmental functions of the Swiss agri-food system face continuously more challenging conditions such as high-wage levels, increasing trade liberalization, demographic change, changing consumer behaviour and increasing health requirements (Godfray et al., 2010).

Food systems, seen as chains from production to consumption, are increasingly analysed in the context of coupled social-ecological systems frameworks (Ericksen, 2008; Liu et al., 2007). Social-ecological systems (SES) frameworks are based on the premise that social and ecological systems are complex adaptive systems that co-evolve through multiple interactions (Folke, 2006) in response to internal or external pressures.

A better understanding of these interactions is crucial for the design of strategies that enhance social as well as ecological outcomes (Schlüter et al., 2014). Dynamic simulation models can serve as tools to explore such interactions and assess the multidimensional impact of policy and management actions over time. Schlüter et al. (2014) developed a stepwise procedure for the design of social-ecological systems models. This procedure exhibits strong similarities to the model building process in system dynamics (e.g., Richardson & Pugh, 1981; Sterman, 2000). Due to the multitude of disciplines involved in the study of a social-ecological system, model development in SES research increasingly uses participatory or transdisciplinary modes of operation (Etienne, 2011; van de Fliert et al., 2011). System dynamics can contribute to this development with the tools and techniques accumulated through group model building and participatory system dynamics modelling research (e.g., Antunes et al., 2015).

The purpose of this paper is thus to build a system dynamics model that represents the Swiss agri-food system as a social-ecological system and to study the twin challenge of aligning food provision with environmental goals. We explicitly link the model characteristics to the corresponding terminology in SES frameworks and the modelling process to the proposed stepwise procedure for developing SES models. We thus illustrate how system dynamics modelling, with its explicit focus on the description of complex interactions between and within subsystems, the representation of feedback effects and the analysis of trade-offs can contribute to the formalization of the social-ecological system framework. We conclude with a discussion of both the potential and limitations of integrating the two approaches.

Conceptual background

A socio-ecological system provides essential services to society such as supply of food, fibre, energy and drinking water (Berkes & Folke, 1998). It can be defined as a set of ecological and social subsystems that are linked through feedback mechanisms (Berkes et al., 2003; Liu, et al., 2007; Ostrom, 2009) and that may be hierarchically linked (Cash et al., 2006). SES are dynamic, complex and adaptive (Berkes, et al., 2003). Inherent to these characteristics is the notion of trade-offs between one set of outcomes, e.g. food provision, at the cost of another (often environmental services), e.g. cleaner water (Carpenter et al., 2009; Ericksen, 2008; MEA, 2005).

The analytical framework of social-ecological systems is useful for food systems because food system activities such as agricultural production, food processing and distribution, as well as consumption are characterized by complex interactions of resources, actors, and institutions (Ericksen, 2008). From a social-ecological systems perspective, an agri-food system with its corresponding food system activities can be represented by different interrelated sub-systems. The general subsystems are (Ostrom, 2009):

- Resource systems such as local agro-ecosystems.
- Resource units such as plants, nutrients, water.
- Governance systems such as rules related to the management of agro-ecosystems.
- Users such as farmers.

These so called first-level subsystems affect each other and are linked to social, economic, and political settings as well as to related ecosystems. Each subsystem is made up of multiple second-level variables such as the size of a resource system, the mobility of resource units, the level of governance, and the number of users (Ostrom, 2009). By linking the different subsystems with each other as well as with their settings and related ecosystems, outcomes such as food provision and environmental performance can be analysed (Ericksen, 2008).

SES modelling is an emerging field to address formalize these relationships. The complexity of social-ecological systems and the lack of a common analytical framework, however, pose significant challenges to SES modelling. SES research is primarily problem-oriented. The majority of existing SES models so far, however, is largely theoretical (Schlüter et al., 2012). Agent based modelling of SES for example, has mostly been applied to 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 modelling is to more explicitly model feedbacks between the social and ecological systems (Schlüter, et al., 2012). The system dynamics model described in the subsequent sections illustrates how system dynamics can contribute to address the current research gaps in SES modelling.

System dynamics model formalizing the SES framework

This section describes the development, analysis and implementation of a system dynamics model that identifies the main challenges for the future development of the Swiss agri-food system and the major knowledge gaps to align food provision with environmental goals. We illustrate the application of the SES framework for the development of a model to answer these questions. Sub-section headings both indicate the step in the system dynamics modelling process and in parentheses the elements in the SES framework that are formalized through this process.

The model was built to inform the further strategic development of Swiss agricultural policy from an integrated perspective (Kopainsky et al., 2014). The model resulted from a participatory and iterative model building, validation and analysis process that started with an existing system dynamics model that analyses global trends in food security and environmental outcomes

(Barilla CFN, 2011). The model building process adjusted this model to the Swiss context and involved stakeholders from the federal ministry of agriculture as well as the federal ministry of the environment, different agricultural research organizations, farmer organizations, extension services, the processing industry and consumer representatives. Stakeholders defined the main outcome indicators and their goal values, the first-level SES subsystems as well as the social, economic, and political settings and related ecosystems. They selected the relevant second-level variables and refined model structures, provided statistical and estimated data for model formulation. Stakeholders also specified and quantified scenarios and policies and discussed policy implications. Stakeholder involvement occurred in the form of interviews, meetings in various formats, workshops and a final one-day conference. The currently on-going subsequent project stage operationalizes model results by the implementation of pilot studies with selected farmers or by the formulation and prioritization of concrete research projects.

Problem definition (identification of outcome indicators)

Progress towards aligning food provision with environmental goals can be measured by the indicators listed in Table 1. Figure 1 plots the development of domestic food production over time (left hand side) and some of the environmental impacts caused by domestic consumption. The figure shows that production has stagnated after an initial increase and, due to population growth, has recently even declined if measured on a per capita basis. At the same time, environmental impacts such as nitrogen losses from domestic production declined with the shift in agricultural policy support in the early 1990s but have since remained stable with no indications of further improvements.

Almost half of the calories consumed in Switzerland are imported. As a consequence, the Swiss agri-food system also has substantial environmental impacts in foreign countries (Liu et al., 2013). Figure 1 thus includes the CO_2 emissions related to domestic consumption, an indicator that represents impacts on related ecosystems.

<< Table 1 about here >>

<< Figure 1 about here >>

System conceptualization (case specific SES framework)

Table 2 conceptualizes the Swiss agri-food system by combining food system activities (first column) with the subsystems defined in the SES framework, i.e., resource systems, resource units, users and governance systems (second column) and settings, i.e., drivers and framework conditions (third column). In addition, the fourth column describes those food systems outcomes that are represented in our case study, generated by the interactions within and across subsystems and settings.

<< Table 2 about here >>

Figure 2 provides an overview of how the different elements of this SES are linked. The figure is an aggregated representation of the main stocks and feedback loops hypothesized to explain the development of food provision (variables with a dark grey background) and environmental outcomes (variables with a light grey background) indicators over time. The figure shows that the model covers the entire agri-food system from the level of agricultural production (plant production and animal production) to processing, transportation and distribution (waste and losses) to the consumer (waste and losses, desired consumption) and that it traces the environmental impacts of these food system activities. This wide system boundary differentiates the model from existing agricultural sector supply models in Switzerland (e.g., Flury et al., 2012; Huber, Rigling, et al., 2013; Peter, 2011) that calculate production and environmental outcomes in very detailed manners but that focus exclusively on agricultural production.

In the upper part of the figure, a set of balancing price loops (*B1a, B1b*) describes plant and animal production and links consumption to agricultural production. Shifts between plant and animal production result from changes in relative prices and from changes in consumption patterns. An increase in the demand for animal products, for example, increases the desired production of animal products and thus the relative attractiveness of animal products. Consequently, more agriculture land is allocated to animal production, which, eventually, results in a higher provision with animal products. This, in turn, lowers the price of animal products and reduces the desired production of animal products. Imports close the gap between total domestic food production and food demand.

The lower part of the figure describes the dynamics of selected economic and environmental resources upon which animal and plant production depend. Nutrients that accumulate in topsoil of agricultural land determine nutrient uptake by food, feed and fodder crops and thus yield. Nutrient uptake increases with plant nutrient uptake efficiency. The same efficiency determines nutrient runoff through leaching and denitrification. Nutrients are replenished through the application of synthetic and organic fertilizer to meet the total nutrient requirements for food, feed and fodder production. Regulations about the total allowable nutrient input (“maximum allowable nutrient input”) limit the operation of this reinforcing feedback loop (*R1*).

Technology and management practices determine the degree to which nutrient input is sourced from renewable (organic) or non-renewable (synthetic fertilizer). Changes in management practices, for example due to changes in crop rotation, tillage or cover crops, increase the return of plant material to the soil. This strengthens the reinforcing organic fertilizing loop *R2a*. Organic fertilizing can also be strengthened through technological advancements in the use of nutrients from animal manure, another renewable source of fertilizer (loop *R2b*). Such technological advancements may stem from nutritional strategies in animal husbandry or from changes in stabling, manure storage and manure distribution. In Figure 2, these advancements are summarized in the variable “efficiency factor manure”. Overall, environmental outcomes are measured at different levels (ammonium emissions from animal husbandry and nutrient runoff, total nitrogen losses, carbon footprint of consumed food).

<< Figure 2 about here >>

Figure 2 provides a visual and transparent illustration of the feedback mechanisms in an SES. In SES terminology, these feedback mechanisms link resource units such as plant and animal production to each other and to their main settings (e.g. population growth, technology improvement). The feedback mechanisms also link subsystems at different levels such as agricultural production, processing and distribution, and consumption. Such cross-level interactions can be represented in a system dynamics model as long as the individual subsystems are defined in an aggregate way. Formalizing feedback among agents within a level that influences outcomes on other levels (e.g. the interaction of different farm types that would endogenously determine the efficiency factor of manure), however, would require advanced modelling techniques, something that is beyond the scope of this paper.

Model formulation and testing

The quantified model consists of the 12 sectors listed in Table 3 (first column). Key stocks and thus key sources of dynamics are the ecological as well as economic resources influencing plant production, the economic resources as well as the animal stocks determining animal production, land stocks changing with changes in land use and the relative attractiveness of animal and plant products, as well as prices that are an important determinant of farmers' decision making (second column). Table 3 also describes the main indicators calculated in each model sector (third column). Model data covers all sectors for the historical time period 1980 to 2010, with varying degrees of completeness and survey frequency for the individual indicators. The "key equations" column in Table 3 indicates that the data was also used to estimate model parameters as evidenced by variables that describe effects (e.g., effect of capital of yield). The most important data sources were:

- The economic accounts for agriculture; farm structure surveys; farm census; structural surveys; agricultural labour force statistics.
- Land use statistics.
- Statistics and estimates of food and agriculture by the Swiss Farmer Union; agricultural reports by the Swiss Federal Ministry of Agriculture.
- Public accounts; contribution catalogue; central analysis; customs statistics.
- Emission data.
- Statistics of population and households; national accounts.
- FAO production and trade data; FAO food balance sheets; FAO nutritional data.

<< Table 3 about here >>

The model differentiates between 30 agricultural products (e.g., food cereals, fruits, vegetables, roots and tubers etc. for plant products and cattle, pork, poultry and dairy for animal products). In this paper, however, we focus on the dynamic complexity caused by different production and consumption developments. Thus, we do not show results for individual products but instead focus on the synergies and trade-offs between food provision and environmental outcomes on national and global levels created by different fields of action.

Structural validation of the model was carried out by numerous and iterative logic, extreme-condition, and boundary tests (Barlas, 1996). Model parameters and input functions were either based on statistical data or input from stakeholder interactions, or estimated from statistical data. Behaviour validation was carried out by extreme-condition and sensitivity as well as behaviour reproduction tests. Behaviour validity can be assessed in the results section that adds historical data to the base run behaviour patterns.

Policy formulation and evaluation

To identify the main challenges for the future development of the Swiss agri-food system and the major knowledge gaps to align food provision with environmental goals, we used the following approach. First, we calibrated the model for a *baseline scenario* that describes the development of the Swiss agri-food system in the time frame 1980 – 2050 under expected settings or framework conditions (population development, overall economic development, climate change, natural disasters, resource scarcity, technical progress) and without fundamental changes in the policies supporting agriculture and the food industry. Assumptions for the definition of the baseline scenario were based on a scenario effort by the Federal Office for Agriculture (BLW, 2010) and more specifically on the intermediate scenario defined therein. This intermediate scenario describes a storyline where resources become gradually scarcer and correspondingly, critical situations increase. Calibrations for this scenario were either taken from existing quantified scenario efforts (such as demographic or economic development scenarios, FAO price forecasts for global commodities, energy price projections) or developed in our stakeholder process.

Second, we identified a variety of *fields of action* conceivable to address the dual challenge of providing more food with less environmental impact. Such fields of action target the different food system activities. Table 4 provides an overview of the fields of action analysed with the model. The choice of fields of action was based on comparable international studies (e.g., Audsley et al., 2010; Godfray, et al., 2010) and on stakeholder input dedicated to the design, selection and quantification of fields of action. The quantification column in Table 4 indicates the variables in the simulation model affected by the fields of action (see also Figure 2) and their quantification. The last column describes the SES sub-systems and their corresponding food system activity that are affected by the fields of action. We chose to speak of fields of action rather than of policies because these fields are much more aggregated (e.g., improve crop yields) than a specific policy such as investment in crop breeding would be.

Third, we analysed the dynamic impact of each field of action and compared *simulation results* with the outcome of the baseline run and the desired food system outcomes (Table 1). It is important to note that in the simulation, no implementation costs for the individual fields of action were considered. Such costs would concern both the costs for the government to compensate farmers for specific services or provide incentives and the costs of the farmers for changing their production to provide specific services.

<< Table 4 about here >>

Results

Baseline scenario: Widening gap between food needs and domestic food production potential

Figure 3 and Figure 4 show the development of food provision and environmental outcomes over time in the baseline scenario. The outcomes are displayed a relative developments, that is, as values relative to the respective goal value for each indicator. A value below 1 indicates a suboptimal situation (that is, more losses/emissions than targeted and less production/self-sufficiency than targeted).

<< Figure 3 about here >>

<< Figure 4 about here >>

In the baseline scenario, population in Switzerland rises up to 9 million by 2050. This has two important implications in our simulation. On the one hand, total consumption by the Swiss population increases. On the other hand, agricultural land is lost to housing and industrial purposes. The loss in productive land directly leads to a decline in the domestic production potential. The widening gap between total consumption and domestic production results in an increase in imports. As a consequence, the self-sufficiency ratio decreases continuously (Figure 3).

With respect to environmental outcomes, Figure 4 illustrates that nitrogen losses from domestic production decrease continuously between 2010 and 2050 and approach the goal value of 74’000 t/year. The main reason for this improvement is the absolute reduction in agricultural production. The ammonia emissions from domestic production are reduced from 2010 to 2050 as well, but less than nitrogen losses. In 2050, ammonia emissions are still well above the goal value of 25’000 t/year. Similar to the reduction in nitrogen losses and ammonia emissions, the emission of CO_2 equivalents from domestic production falls with the decreasing domestic production. However, if the CO_2 equivalents of imports (and thus the foreign production for domestic consumption) are added to domestic production, the total emission of domestic consumption increases from 2010 to 2050. Although data on nitrogen losses and ammonium emissions from imports are not available it is likely that the total nitrogen losses and ammonium emissions caused by domestic consumption increase in a way similar to that of greenhouse gas emissions.

Overall, our baseline scenario illustrates the widening gap between food needs and the domestic food production potential. The declining domestic production has beneficial environmental effects in Switzerland. However, these beneficial environmental outcomes in Switzerland are offset by increasing imports and their corresponding environmental impacts in other countries. Thus, the baseline scenario shows important off-site effects from changing production and consumption patterns and a trade-off between environmental and food provision goals.

Fields of action: Synergies and trade-offs between food provision and environmental outcomes

The model simulations identify the leverage of the identified fields of action to address the challenges identified in the baseline scenario. Due to space restrictions, the results from model simulations are summarized in the form of a table. Towards the end of this sub-section, we illustrate behaviour over time graphs for a particularly interesting simulation run. Table 5 summarizes simulation results in terms of absolute impact of a field of action (the percentage deviation from the goal value in 2050) and relative impact of a field of action (whether the field of action improves or deteriorates the situation reached under baseline conditions in 2050). The table lists the value for each indicator relative to its goal value. A value below 1.00 indicates a suboptimal situation (that is, more losses/emissions than targeted and less production/self-sufficiency than targeted). The shading of the cells visualizes whether the indicator experiences an improvement or deterioration with regard to the baseline situation in 2050.

For some fields of action such as consumption, waste and losses, use of non-renewable inputs, as well as productivity, the table lists the simulation results of different calibrations: In these cases, the first calibration is based on stakeholders' assessment of changes that can realistically be assumed (values listed in Table 4). The second calibration is based on model simulations and represents changes that are necessary to reach one or several policy goals (e.g., keeping imports at their 2010 value in the case of reductions in food waste and losses) or that explore the impact of more drastic policy changes (e.g., decreasing the consumption of animal products by 20% instead of only 10%).

<< Table 5 about here >>

Consumption patterns and reduction of food waste and losses

The simulation results for the field of action regarding consumption patterns reveal a trade-off between environmental and food provision outcomes. Table 5 shows that the changes in consumption patterns have positive environmental outcomes both within Switzerland as well as abroad. The food provision outcomes of these changes, however, are less obvious. The decline in demand for animal products results in a corresponding increase in the demand for plant products. Due to the limited agronomic potential of Switzerland, this increase in demand for plant products cannot be met by domestic production but instead needs to be covered by increasing imports. This leads to an overall increase in imports and thus to a decline in self-sufficiency. The limited availability of the stock of arable land (a sub-set of the total agricultural land) prevents changes in consumption patterns from aligning environmental outcomes with some food provision outcomes in Switzerland.

The reduction of food waste and losses, on the other hand, creates synergies between food provision and environmental outcomes. It reduces the need for imports and thus also the environmental impact of the imported products. With reduced imports, self-sufficiency increases. However, reaching food provision goals such as keeping self-sufficiency at its 2010 levels would imply doubling what experts estimated to be a realistic reduction potential in waste and losses.

Changes in productive land, regulations regarding the use of non-renewable inputs

Regulations regarding the use of non-renewable inputs and an increase in the proportion of ecological compensation areas are relatively one-sided. They improve the values of the domestic environmental indicators. However, they also affect the production volume since the productivity of inputs is reduced. This requires higher imports. Making nutrients from manure and other organic sources better available and more widely usable can compensate the negative production impacts. Such compensation measures are able to reduce the trade-off between food provision and environmental outcomes and strengthen the *R2* organic fertilizing loop.

Emissions from plant and animal production

Another possibility for reducing the trade-off between food provision and environmental outcomes lies in the reduction of emissions from plant and animal production, which has positive environmental impacts without compromising production.

Productivity increases through plant breeding

Yield increases resulting from breeding are important for maintaining total domestic production stable on continuously decreasing amounts of agricultural land. However, productivity increases also increase the demand for nutrients from fertilizer and an increased use of fertilizer leads to an increase in nutrient losses. Yield improvements without compensating measures thus create a trade-off between food provision and some environmental outcomes. The increased productivity reduces the need for imports with their environmental impacts.

Combinations

The results so far have shown that no field of action alone is able to lead to significant improvements in both food provision and environmental outcomes with regard to their baseline values. We thus also tested four different combinations of fields of action.

The first two combinations integrated agronomic fields of action that double the realized yield relative to the baseline scenario while at the same time reducing the environmental impact of food production by keeping the use of non-renewable inputs constant and, in the case of combination two, reducing emissions from plant and animal production. Combinations one and two show that major synergies between food provision and environmental outcomes can only be created if the reinforcing fertilizing loops (*R1, R2* in Figure 2) can be strengthened through integrated production systems.

Combination three reveals that fields of action that lie outside agriculture such as consumption patterns and the reduction of food waste and losses are also able to create synergies between food provision and environmental outcomes. However, especially the food provision impacts remain lower than if such fields of action are combined with agronomic improvements.

For this reason, combination four added a reduction in food waste and losses by 20% to the agronomic combinations. Such a combination leads to significant improvements in all the indicators relative to their baseline value. The reduction in waste and losses is necessary to bring the self-sufficiency and import indicators close to their respective goal values so that all food provision and environmental indicators experience considerable improvements.

Discussion

The model simulations presented in the previous section showed that under baseline conditions, the gap between food needs and domestic food production potential in Switzerland continues to grow and that the current agri-food system creates trade-offs between food provision and environmental goals. Within existing production systems, increases in production are accompanied by increases in environmental impacts. Decreases in production, on the other hand, create important off-site effects as the environmental impacts occur in the countries that provide the imported food. The model simulations also showed that the Swiss agri-food system has the potential to create synergies between food provision and environmental outcomes in the long run. Realizing this potential, however, can only be achieved through the combination of several fields of action. In addition, the following factors need to be considered:

- Special efforts are necessary to go considerably beyond currently existing or anticipated improvements in the area of production and resource conservation.
- Only an integrated perspective on the entire agri-food system makes it possible to realize the above mentioned potential. Yield improvements and the development of more sustainable production systems have important leverage from within agriculture. However, these fields of action need to be complemented by fields of action outside agriculture such as reductions in food waste and losses or changes in consumption patterns.
- An integrated perspective and the required special efforts make increased cooperation between and within research and development, planning, consulting and practice indispensable.

Grounding the challenges for the future development of the Swiss agri-food system in the SES framework and at the same time formalizing this framework using system dynamics proved to be useful in several respects. First and contrary to existing agricultural sector models in Switzerland, our system dynamics model represented food system activities beyond agricultural production such as processing, distribution and consumption. Ingram et al., (2010) provide compelling evidence that local solutions need to take global trade-offs into account. Our analysis therefore included national and global environmental outcomes of development trends and fields of action, that is, impacts on related ecosystems. Due to data restrictions, this was only possible for greenhouse gas emissions. Provided data availability, global food provision outcomes might be added to the calculation of national food provision outcomes.

Second, the explicit representation of feedback mechanisms in our model allowed evaluating the relative contributions of different fields of action that provide exogenous input such as the reduction of food waste and losses or shifts in consumption patterns and fields of action that strengthen (reinforcing) feedback loops, e.g. through increases in the efficiency factor of manure. Synergies between food provision and environmental outcomes can only be realized if the reinforcing organic fertilizing loops can be strengthened. However, model analysis also revealed that exogenous inputs are necessary, e.g., in the form of yield improvements.

Conclusions

The complexity of social-ecological systems and the need to integrate knowledge, theories and approaches from different disciplines pose considerable challenges for the development of SES systems models (Schlüter, et al., 2014). This paper described the conceptualization, formalization and analysis of a system dynamics model that studied the challenge of aligning food provision with environmental goals in the Swiss agri-food system.

One of the main research needs in SES modelling, according to Schlüter et al. (2012), is the explicit representation of feedbacks between social and ecological systems. Our case study illustrated the contribution that system dynamics can make in this respect. Knowledge about agronomic processes and data about the agri-food system are abundant in Switzerland. The simulation model integrated the variables and linkages that comprise the relevant SES subsystems and by doing so provided a new, more parsimonious view of the Swiss agri-food system. The simulation model with its focus on accumulations, feedback loops and non-linearities helped characterize the range of outcomes and the trade-offs that the food system activities generate. In that sense, the model provided a transparent and internally consistent case specific social-ecological systems framework that is firmly grounded in data and previous work, also reaching a new level of specificity concerning the feedback loops that link the subsystems and the complex behaviours as well as the manifold trade-offs they give rise to (Kopainsky & Luna-Reyes, 2008; Repenning, 2002).

Another contribution that system dynamics can make to SES modelling, particularly in the context of food systems, was outside the scope of the case study. This contribution would be the analysis of different sources of food system vulnerabilities to economic, political, social and environmental shocks (e.g., Adger, 2006; Eakin, 2010 ; Leichenko & O'Brien, 2008). An important source of vulnerability lies in the management of the stocks in a food system such as natural resource stocks as well as the stocks of produced food, processed food, and food available for consumption. The explicit representation of stocks and flows in system dynamics models that determine residence times of food in these stocks or the health of the natural resource base can provide indications about the sensitivity of these shocks to disruptions in the flows into and out of them.

A limitation to system dynamics models in this context is the fact that resilience of a system at a particular level, e.g., resilience of food provision at the national level, will depend on influences at levels above and below (Gunderson & Holling, 2002; Holling, 2001). Our model was able to represent interactions between subsystems and to integrate exogenous parameters from different levels. It also represented feedback mechanisms between levels (such as agricultural production and consumption) as long as the individual levels were modelled in an aggregated way. Further spatial disaggregation of the biophysical and decision making processes, however, would require the use of agent based models, which are widely used in SES analysis (e.g., Heckbert et al., 2010; Huber, Briner, et al., 2013; Le et al., 2012; Miller & Page, 2007; Schlüter, et al., 2012; Tesfatsion & Judd, 2006). Such disaggregation shifts the focus away from the interaction of reinforcing and balancing feedback loops but can be important for the design and calibration of individual policy instruments. The effectiveness of policies that strengthen the reinforcing organic fertilizing loop in our model depends to a considerable extent on the spatial distribution of livestock, an aspect that is difficult to implement in a system dynamics model. Similarly, the effectiveness of policies that encourage the implementation of technologies and management practices for improving the efficiency factor of manure and plant uptake efficiency is tightly related to agricultural structures and the endowment of farms with production factors such as land and capital.

No single method can accomplish integrated, cross-scale and cross-level modelling of social-ecological systems. Instead, SES research needs to rely on hybrid frameworks where multiple qualitative and quantitative methodologies are applied, making use of a combination of existing quantitative sources, case studies, and stakeholder input (Engle et al., 2013; Ericksen et al., 2009; Janssen & Anderies, 2013). This paper illustrated how system dynamics models add to the insights that can be gained form other modelling approaches and how they can be used to systematically explore the consequences of assumptions made by conceptual frameworks and stakeholder input.

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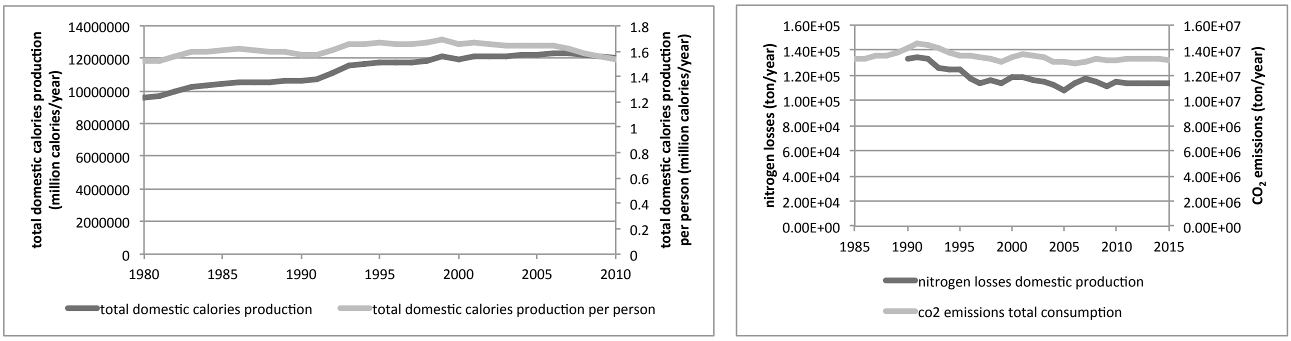
Figures

Figure 1: Production and environmental performance of the Swiss agri-food system between 1980 and 2010.

a) Production

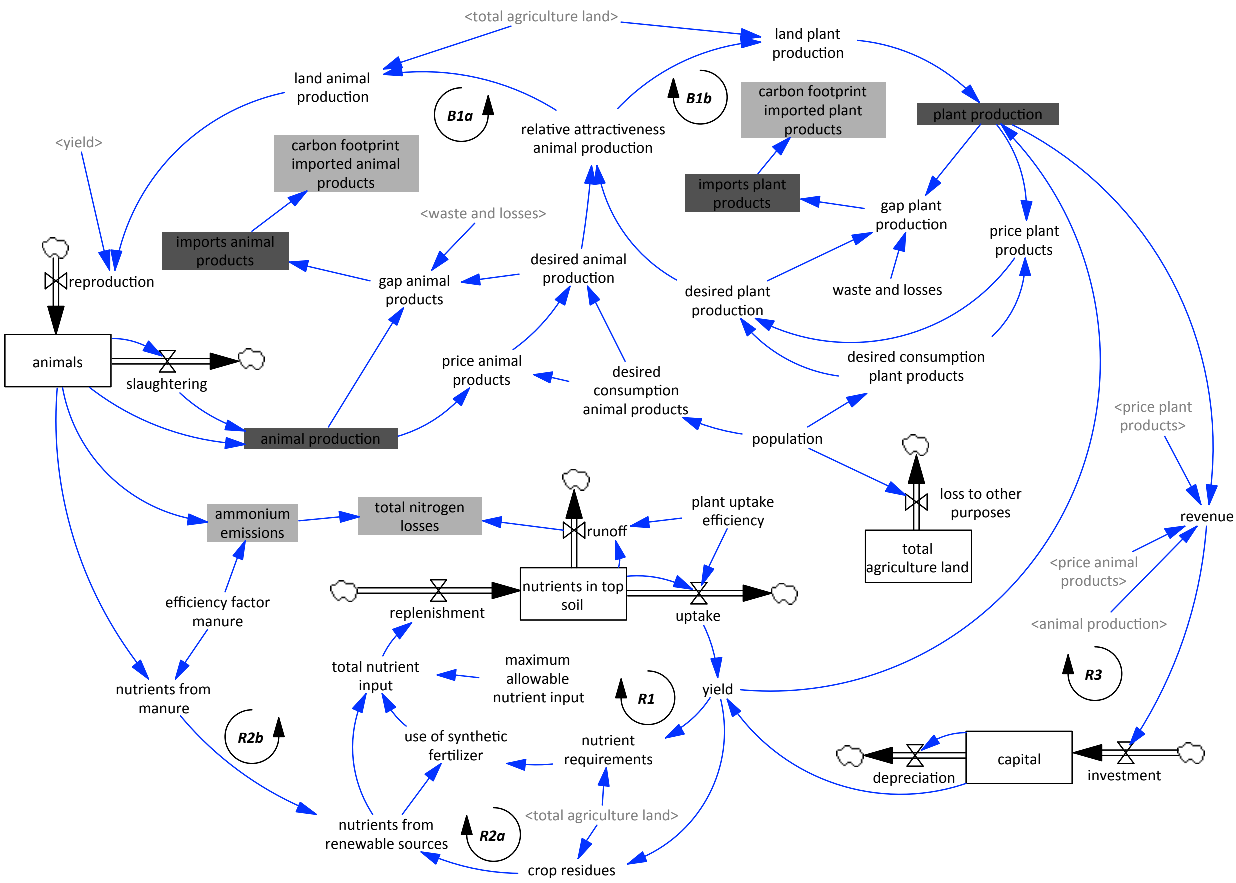
b) Environment/resource efficiency



Data sources: Swiss Farmers Union (various years); Swiss Federal Office for Statistics (various years).

Nitrogen losses between 2010 and 2015: estimates included in the official statistics from the Swiss Federal Office for Statistics.

Figure 2: Main feedback loops linking the different food system activities with their corresponding SES sub-systems and determining food system outcomes.



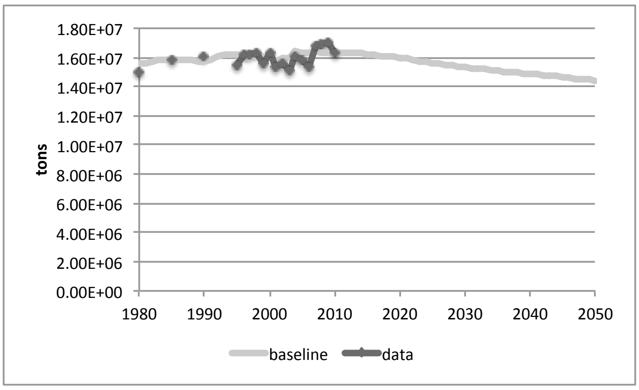
Notes:

- B1a/b: balancing price loops
- R1: production reinforcement through fertilizing

- R3: production reinforcement through investment
- R2a/b: organic fertilizing

Figure 3: Food provision outcomes in the baseline scenario

a) Domestic food production (incl. grass)



b) Self sufficiency

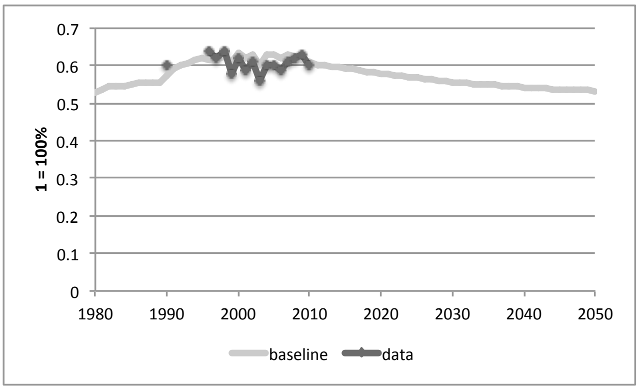
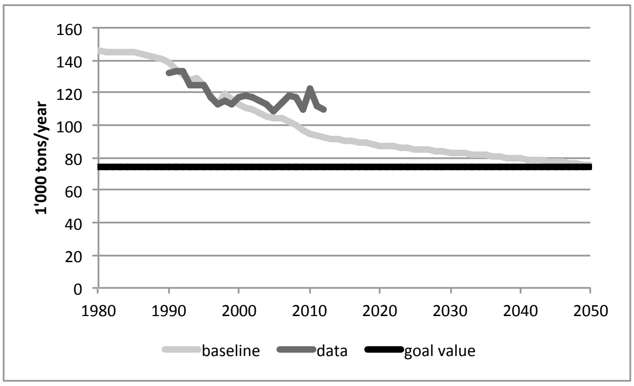
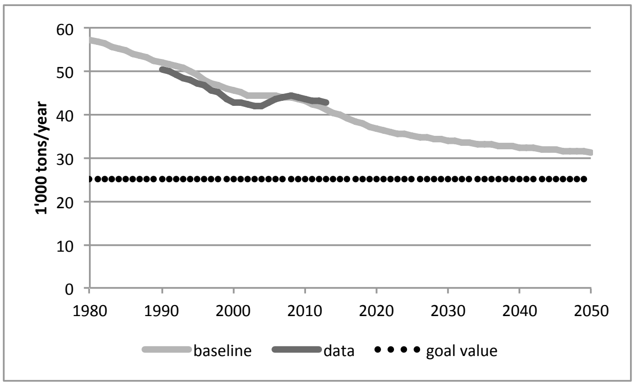


Figure 4: Environmental outcomes in the baseline scenario

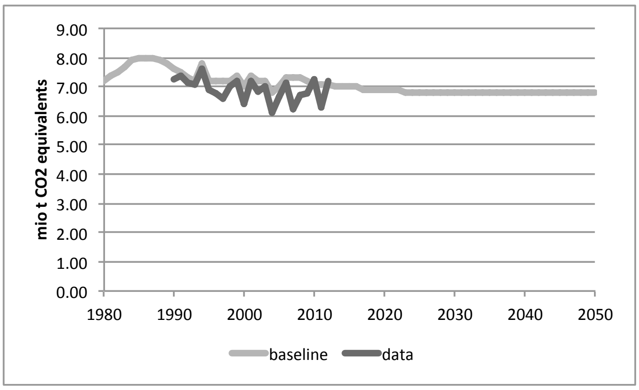
a) Nitrogen losses



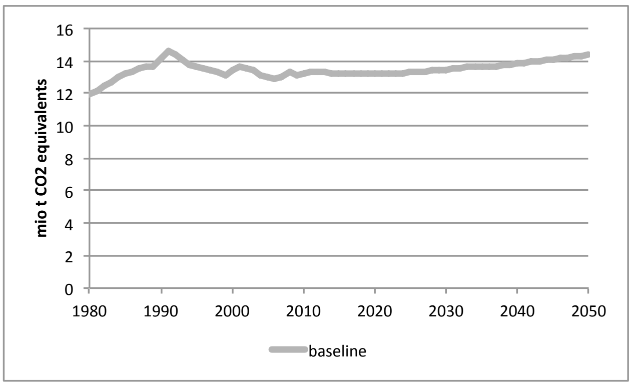
b) Ammonium emissions



c) Greenhouse gas emissions domestic production



d) Greenhouse gas emissions total domestic consumption



Tables

Table 1: Food provision and environmental performance indicators and goals

Area	Indicator	Goal value	Explanation

Environ mental performa nce	Nitrogen losses	74'000 tons/year	Source of goal value: BLW, 2004.
	Ammonium emissions	25'000 tons/year	Source of goal value: BAFU & BLW, 2008.
	Greenhouse gases (CO_2 equivalents; carbon footprint)		Qualitative goal: reduction of emissions.
Food provision	Domestic food production		Implicit goal in agricultural policy: maintenance at today's level.
	Imports		Implicit goal in agricultural policy: maintenance at today's level.
	Self-sufficiency ratio		The domestic production and self-sufficiency goals are not entirely consistent which makes it impossible to define an implicit goal value for imports. An increase in the amount of imports is evaluated negatively as the global agri-food system will have to provide up to 70% more of food products by 2050 (e.g., Godfray, et al., 2010) so that it is difficult for Switzerland to simply export its own food insecurity.

Table 2: The Swiss agri-food system as a social-ecological system as represented in the system dynamics model

Food system activities	**SES sub-systems**	**Main settings (drivers and framework conditions)**	**Food system outcomes**
Agricultural production	**Resource system**: Local agro-ecosystems (land cover and soils) **Resource units**: Plant production, animal production, water availability, nutrient availability and cycling, biodiversity, waste and losses **Users**: Farmers **Governance system**: Swiss agricultural policy	Socioeconomic: Trade regulations, world market prices, oil and energy prices, science and technology, public infrastructure, energy input Environmental: Climate change, decline in agricultural land	Nitrogen losses Ammonium emissions Emission of greenhouse gases through domestic production Domestic production
Processing and distribution	**Resource system**: Global agro-ecosystems, global supply chains **Resource units**: Plant and animal products, waste and losses **Users**: Food processing industry and retailers **Governance system**: Global markets, Swiss market regulations	Socioeconomic: Economic growth, international relations, global energy system (oil and energy prices), science and technology, public infrastructure Environmental: Resource scarcity, climate change	Emission of greenhouse gases through domestic production & imports
Consumption	**Resource system**: National and global agro-ecosystems, national supply chains **Resource units**: Food consumed, food waste	Socioeconomic: Economic growth, population growth, changes in consumption patterns	Emission of greenhouse gases through domestic production & imports Self-sufficiency ratio

	Users: Consumers **Governance system**: Consumer protection regulation		Imports

Table 3: Summary of model specifics

Model sector	**Key stocks**	**Outcome indicator of interest**	**Key equations**
Plant production	Ecological resources: plant genetic variety, nutrients in top soil, available water, soil organic matter, biodiversity Economic resources: capital, labour, knowledge	Plant production (ton/year)	Yield = INITIAL YIELD*effect of capital on yield*effect of employment on yield*effect of knowledge on yield*effect of available water on yield*effect of nutrient uptake on yield*effect of biodiversity on yield*effect of plant genetic variety on yield Where, e.g., effect of capital on yield = relative working capital per hectare^ELASTICITY OF YIELD TO CAPITAL
Animal production	Economic resources: capital, labour Animal stock	Animal products (ton/year)	
Food demand		Desired consumption plant products (ton/year; kCal/year) Desired consumption animal products (ton/year; kCal/year)	
Import		Net imports plant products (ton/year) Net imports animal products (ton/year)	Target import quantities = SMOOTH N(estimated food production gap, TIME HORIZON FOR ESTABLISHING FOOD PRODUCTION GAP TREND, INITIAL target import quantities, 1)
Food prices		Price plant products (CHF/ton) Price animal products (CHF/ton)	Price = INITIAL PRICE PER TON*effect of production costs on indicated price*effect of international food consumer prices on indicated price*effect of consumption on indicated price
Processing and consumption		Waste and losses share (%)	
Production change		Relative attractiveness animal products (%)	Indicated food production in tons = INITIAL INDICATED FOOD PRODUCTION IN TONS*

			effect of direct payments on production change*effect of production costs on production change*effect of relative prices on production change
Land use	Settlement land Forest area Meadows and pasture Arable land and permanent crops		Indicated arable land = arable land by crop*indicated food production change
Economic accounts		Food production costs per ha (CHF/ha/year)	
Energy use		Total energy use (Mj/year)	
Emissions and environmental goals		Ammonium emissions (ton/year) Total nutrient losses (ton/year) CO_2 emissions domestic production (ton/year) CO_2 emissions domestic production and imports (ton/year)	
Food provision goals		Domestic production (ton/year; kCal/year) Imports (ton/year; kCal/year) Self-sufficiency (%)	

Table 4: Potential fields of action for a transformation of the Swiss agri-food system

SES sub-system	Field of action	Basis	Quantification
Resource unit within consumption	Consumption patterns	The production of animal products is less efficient and causes more emissions than that of plant products. A reduction in the consumption of animal products also has beneficial health impacts.	Reduction in the desired consumption of animal products by 10% (relative to 2010), in the desired consumption of plant products by 10% until 2050.
Resource unit within agricultural production, processing and distribution, consumption	Food waste and losses	A third of the food produced for Swiss consumption is lost along the food value chain (Beretta et al., 2013).	Reduction of waste and losses by 20% (relative to 2010).
Resource system	Productive	A possibility to reduce the environmental	Increase in the share of ECA

within and driver of agricultural production	land	impact of agricultural production is a further increase in the percentage of ecological compensation areas (ECA) each farmer has to set aside. On the other hand, it is conceivable to decrease the compulsory share of ECA in order to strengthen the production function of agriculture.	from currently 7% to 10%. Decrease from 7% to 5%.
Resource unit and governance system within agricultural production	Use of non-renewable input	One option to reduce nitrogen losses to the environment is the restriction on the use of non-renewable resources such as synthetic fertilizer.	Restriction on the use of synthetic fertilizer until the goal of 74'000 t/year is reached.
Resource unit within agricultural production	Use of renewable input	More environmentally sustainable production systems exploit biological nitrogen fixation, efficiently use organic fertilizer and use it to replace synthetic fertilizer.	Replace reductions in the use of synthetic fertilizer by fertilizer from renewable sources.
Resource units within agricultural production	Emissions from plant production	Another option to reduce nitrogen losses to the environment is to increase the efficiency of non-renewable inputs such as synthetic fertilizer through the implementation of best practices in crop production losses (cf., Bundesarbeitskreis Düngung, 2003).	Plant uptake efficiency at 85% until 2050.
Resource units within and drivers of agricultural production	Emissions from animal production	An increase in the efficiency of animal manure can be facilitated either by nutritional strategies in animal husbandry (Bracher et al., 2011) or technical measures such as stabling, manure storage and manure distribution (Peter, 2011).	Increase in efficiency factor manure by 20% until 2050.
Drivers of agricultural production	Productivity	Yield growth in the past has contributed significantly to maintaining domestic production on gradually decreasing agricultural land. However, the realized yield increases have slowed down considerably in the last 40 years.	Increase in potential yield of all crops by 0.5% per year.

Table 5: Summary of food provision and environmental outcomes of different fields of action (percentages of the respective goal values)

	Nitrogen losses	Ammonium emissions	CO_2 emissions domestic production	CO_2 emissions total domestic consumption	Domestic production (calories)	Self-sufficiency (calories)	Imports (calories) *

	Nitrogen losses	Ammonium emissions	CO_2 emissions domestic production	CO_2 emissions total domestic consumption	Domestic production (calories)	Self-sufficiency (calories)	Imports (calories) *
Baseline	0.98	0.80	1.05	0.92	0.93	0.89	(1.27)
Consumption – 10%	1.02	0.85	1.07	0.95	0.93[1]	0.87	(1.33)
Consumption – 20%	1.06	0.91	1.08	0.97	0.92	0.85	(1.39)
Waste – 20%	0.98	0.80	1.05	0.93	0.93	0.94	(1.14)
Waste – 30%	0.98	0.80	1.05	0.93	0.93	0.96	(1.07)
Waste – 40%	0.98	0.80	1.05	0.94	0.93	0.99	(1.00)
Productive land – 10% ECA	0.99	0.80	1.07	0.92	0.91	0.88	(1.29)
Productive land – 5% ECA	0.97	0.80	1.04	0.92	0.94	0.90	(1.26)
Non-renewables	1.00	0.80	1.05	0.92	0.93[1]	0.89[1]	(1.28)
Non-renewables & renewables	0.98	0.80	1.05	0.92	0.93	0.89	(1.27)
Emissions – only plant production	1.15	0.80	1.05	0.92	0.93	0.89	(1.27)
Emissions – only animal production	1.00	0.88	1.05	0.92	0.93	0.89	(1.27)
Emissions – all production	1.15	0.88	1.05	0.92	0.93	0.89	(1.27)
Productivity – 200%	0.97	0.80	1.15	0.96	0.97	0.92	(1.24)
Productivity – 400%	0.91	0.80	1.09	1.02	1.05	0.97	(1.17)
Combination 1 – productivity 200% & non-renewables & renewables	1.16	0.80	1.07	0.96	0.97	0.92	(1.24)
Combination 2 – combination 1 & emissions all production	1.18	0.84	1.06	0.96	0.97	0.92	(1.24)
Combination 3 – consumption 10% & waste 20%	1.02	0.85	1.07	0.96	0.93	0.92	(1.18)
Combination 4 – combination 2 & waste 20%	1.18	0.84	1.06	0.96	0.97	0.96	(1.11)

Notes:

*Imports measured as percentage of their 2010 level

[1]Differences not visible due to rounding

Cells in light grey: field of action improves indicator 2050 relative to its baseline value 2050

Cells in dark grey: field of action deteriorates indicator 2050 relative to its baseline value 2050

Cells in white: no change induced by the field of action relative to the baseline scenario