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A food systems perspective for food and nutrition security beyond the post-2015 development agenda

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Abstract

This paper proposes a framework for dealing with the complexity of sustainable food systems for guiding implementation, monitoring and evaluation of Sustainable Development Goal number 2 “End hunger, achieve food security and improved nutrition and promote sustainable agriculture”. The framework combines a food systems approach with systems analysis and modelling techniques and helps identifying areas in need of further clarification for an effective post-2015 development agenda. Furthermore, the paper explains how the proposed framework can be used in developing theory of transformations and in formulating indicators that control for dynamic complexity. The paper also emphasizes the importance of building comprehensive monitoring systems for this purpose.

Keywords

food systems; monitoring and evaluation; model-based policy analysis and design; post-2015 development agenda; sustainable development goals; system analysis and modelling;

Introduction

Providing food for an expanding and more demanding world population remains a major challenge now and in the future. The majority of current agricultural and food systems is not sustainable; they are over-reliant on non-renewable external inputs, produce high levels of greenhouse gas emissions, and have negative impacts on soils and biodiversity, farm animal welfare, nutrition and public health outcomes, cause high levels of waste, and exhibit a low level of resilience against external shocks (e.g., Garnett et al., 2013; Rockström et al., 2009). Hence, tackling the problem of food security requires transformations in local, national and global agricultural and food systems while, at the same time, addressing environmental and social issues (e.g., Ingram et al., 2010).

Such transformations are also pushed forward by the UN Sustainable Development Goals (SDGs) that replaced the Millennium Development Goals (MDGs) in 2016. The SDGs are a set of coherent, aspirational goals (Norström et al., 2014) that are further specified by targets and indicators. Goals are broad, qualitative statements about objectives. Indicators, on the other hand, are quantitative measures that assess the progress towards or away from a stated goal. Targets use indicators to make goals specific with endpoints and timetables (Parris & Kates, 2003).

In this paper, we propose a framework for dealing with the complexity of sustainable food systems in order to support the implementation of the second SDG “End hunger, achieve food security and improved nutrition and promote sustainable agriculture”. A clearer understanding of the goal’s scope and its interrelated targets and indicators can help evaluating progress towards the required sustainability transformations on local, national and global levels. The framework combines a food systems approach with systems analysis and modelling techniques. A food systems approach connects the activities of food producers, processors, distributors, retailers and consumers to food security, as well as social, and environmental outcomes, and frames these activities as dynamic and interacting processes embedded in social, political, economic, historical and environmental contexts (Ericksen, 2008; FAO, 2008; Ingram et al., 2010). Systems analysis and modelling techniques drawn from complexity science provide complementary ways not only to evaluate multidimensional and long-term impact pathways of policy and management actions, but also to monitor their implementation (Hammond & Dubé, 2012).

One important shortcoming of the MDGs was that they emphasized to a large extent the human aspects of development over the importance of natural capital and ecosystem services. They also lacked a theory of change (transformation) and an associated mechanism for delivering outcomes (e.g., Waage et al., 2010) ultimately creating isolated goals (Haddad, 2013). Here, we demonstrate that a food systems approach, on the other hand, can make a considerable contribution at the level of developing, implementing and monitoring interrelated targets and corresponding indicators for the post-2015 development agenda. Instead of proposing specific indicators, we highlight how the principles of a food systems approach and of systems analysis and modelling techniques can provide a rigorous framework for the establishment of a development agenda. Furthermore, subsequent policy and management actions and their corresponding evaluation strategies can be designed based on this framework.

Although the analytical framework proposed is appropriate for the establishment, implementation, monitoring and evaluation of a post-2015 development agenda in location- and case-specific food systems, effective transformations towards food and nutrition security and sustainable agriculture also require careful consideration of political agency and negotiation of power relations. While this is beyond the scope of this paper, it is important to emphasize that the analytical framework presented here needs to be combined with political ecology (e.g., Akram-Lodhi, 2013) and other approaches in concrete implementation settings (e.g., Avelino & Wittmayer, 2015; Foran et al., 2014).

Accordingly, the remainder of this paper is organized as follows. First, we explain the food systems approach and detail how systems analysis and modelling techniques can help frame food systems in the post-2015 development agenda. We then compare the targets of the second SDG with the implications of our framework and derive implications for the implementation of an effective post-2015 development agenda.

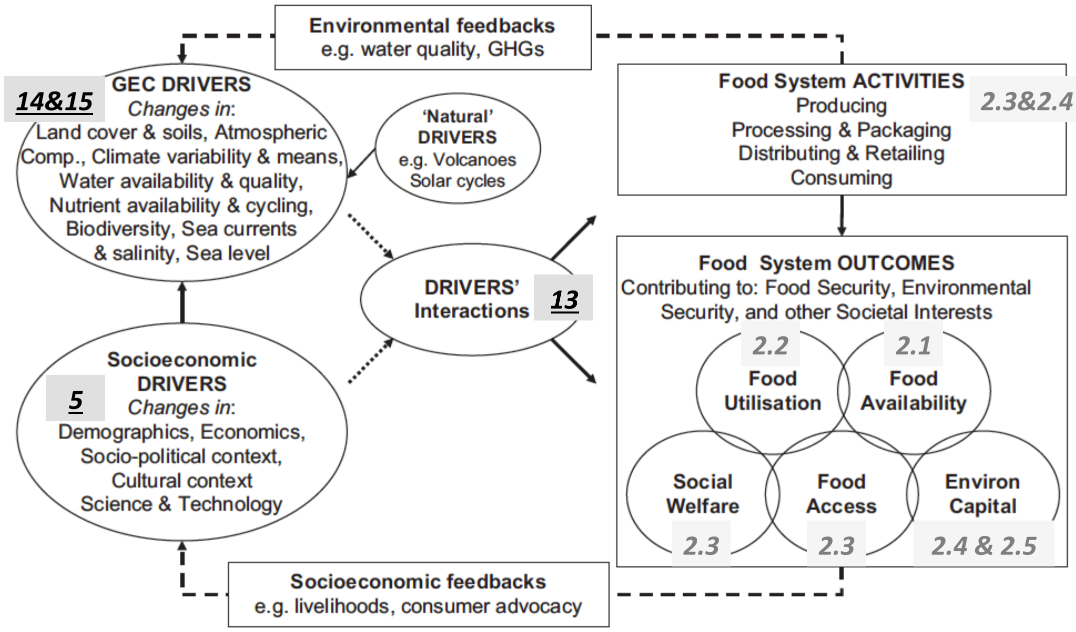
A framework for guiding implementation, monitoring and evaluation of SDG 2

Food systems, at a minimum, comprise sets of activities involved in food production, processing and packaging, distribution and retail, as well as consumption (Ericksen, 2008). These activities lead to a number of social, environmental and food security outcomes such as food availability, access and utilization, but also the provision of ecosystem services or the accumulation of human, financial and social capital. Food system activities and outcomes eventually result in processes that feed back to environmental and socioeconomic drivers (Ericksen, 2008; FAO, 2008). The drivers, in turn, describe the bio-geophysical as well as the social, economic and political environments that determine how food system activities are performed.

Explicitly linking food system activities to their food security, environmental as well as social welfare outcomes is important as food system outcomes result from a complex set of interactions in multiple domains. Feedback from food system drivers and activities are of particular concern as they may have unintended social and environmental consequences, for example, when the production of biofuels in one place creates unintended consequences elsewhere (such as carbon leakage (Davis et al., 2011), biodiversity losses (Lenzen et al., 2012), and pollution (Bollen et al., 2010), or when farmers draw their financial and other assets below a critical threshold (after a shock) and fall into natural resource-based poverty traps (Stephens et al., 2012).

Figure 1 illustrates the interconnections between food system activities, outcomes and drivers and demonstrates the big feedback processes linking these food system elements. The figure also shows how SDG 2 relates to food system activities, outcomes and drivers by positioning the corresponding SDG 2 target number close to relevant food system elements.

Figure 1: Food systems and SDG 2 targets (adapted from Ericksen, 2008: 239).



Notes: The figure positions the targets specifying SDG2 (bold and italic dark grey numbers) by placing them close to relevant food system activities, outcomes and drivers. The figure also highlights important interlinkages between SDG 2 and other SDGs by referencing other SDGs (bold, italic and underlined black numbers) inside the diagram. For more details on SDG 2 targets, cf. Appendix 1, and for more information on SDGs in general, cf. United Nations, 2016.

The main feature of a food systems approach is the explicit representation of complexity. Complexity in this context includes: interactions between the use of natural resources and the environment at multiple levels of scale (Cash et al., 2006; Hammond & Dubé, 2012; Kok & Veldkamp, 2011); feedback effects that result in complex and often non-linear dynamics (Liu et al., 2007; Ostrom, 2009); and the emergence of trade-offs between one set of services (for example food production) at the cost of another (for example cleaner water) (Carpenter et al., 2009; Ericksen, 2008; MEA, 2005). Due to the complex and non-linear dynamics of food systems, feedback developments and accumulation processes must be closely observed to keep critical thresholds under control (Griggs et al., 2013; Neufeldt et al., 2013).

Systems modelling approaches such as dynamics provides appropriate methodologies in this context. System dynamics is a computer-aided approach to policy analysis and design. It is applied to dynamic problems arising in dynamic systems characterized by interdependence, mutual interaction, information feedback, and circular causality (e.g., Richardson & Pugh, 1981; Sterman, 2000). Conceptually, the feedback concept is at the heart of the system dynamics approach. A feedback loop exists when results of some action in a system eventually impact on its point of origin, potentially influencing future action. System dynamics distinguishes between reinforcing and balancing feedback loops. Balancing loops can be variously characterized as goal-seeking, equilibrating, or stabilizing processes. Reinforcing loops are sources of growth or accelerating collapse and thus, act disequilibrating or destabilizing.

Feedback loops link food system activities with their environmental as well as their socioeconomic drivers. Feedback loops are also at the heart of various types of development traps such as natural resource traps, poverty traps, and combinations thereof. The poverty trap, for example, describes a situation where households with poor asset endowments (for example capital) are unable to invest in or use productive assets, which continuously exacerbates food insecurity. Poverty traps often involve the depletion of natural capital in order to sustain food production (Perrings, 1989) which, in turn, lowers agricultural labour and land productivity, and discourages capital-poor farmers from rebuilding and maintaining the natural resource base (Marenya & Barrett, 2009). Thresholds in those assets define whether a reinforcing feedback loop acts as a vicious or virtuous cycle and inform, for example, whether households are unable to escape from poverty and associated food insecurity (Stephens et al., 2012).

Feedback loops are characterised by accumulation and delays for entities that can be stocked up or depleted. Accumulations in feedback systems are variously called stocks, state variables, or levels. The rates of increase or decrease of stocks are called flows (e.g., births and deaths, or revenue and expenditure). Stocks and flows track accumulations of material and information through a system (for example inventories of products, populations, or financial accounts). Decisions in a system are based on the available stocks and can alter the rates of flow. This, in turn, affects the stocks with some delay while closing feedback loops. Delays create instability in dynamic systems.

Accumulation is central to food systems (Brzezina et al., 2016; Stave & Kopainsky, 2015). 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 including production, processing and distribution. Managing accumulations is therefore 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). Managing accumulations means comparing a stock to a desired state and introduce corrective action if needed. Consequently, decision makers must regulate the inflow rate to compensate for the outflow rate or vice versa. Often there are delays between corrective actions and their effects as perceived by the decision makers.

The food systems approach combined with systems analysis and modelling tools outlines our framework for guiding implementation, monitoring and evaluation of SDG 2. However, it is important to note 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 solutions to the challenges and problems arising in them (Janssen & Anderies, 2013; Ostrom et al., 2007; Ostrom, 2009). Our explanations here focus on a discussion of relevant insights that arise from a feedback perspective on food systems rather than on the identification of case-specific policy and management actions.

Based on these explanations, a few questions need to be considered when moving from the targets in SDG 2 to designing and implementing location- and case-specific development agendas for food and nutrition security and sustainable food systems:

- Is there a clear theory of transformation that links food system activities, outcomes and drivers? More specifically:

    - Are the social and ecological processes underlying food system activities identified?
    - Is it known what outcomes (for example, food security) these activities generate?
    - Are changes in outcomes and their influences on food system drivers distinguished (for example, socio-economic context)?
    - Are changes in food system drivers and their effects on the social and ecological processes underlying food system activities recognised?
- Do the targets and particularly the indicators adequately control for dynamic complexity? More specifically:
    - Are important sources of accumulation identified and operationalized such that proper stock management is possible?
    - Are there indicators that control for potential unanticipated consequences of policy and management actions arising from the unfolding of feedback processes?

Framing food systems in the post-2015 development agenda

Sustainable Development Goal 2 on zero hunger includes references to food system outcomes, activities and drivers (Appendix 1) and hence covers all the elements of a food systems approach. One or two indicators further specify each target (Economic and Social Council, 2015). The theory of transformation underlying the targets and indicators is, however, difficult to identify. The proposed targets fail to describe an operational framework that monitors outcomes on the basis of activities and drivers and that links them in feedback loops. In Appendix 1, targets 2.1, 2.2 and the first half of 2.5 state desired food system outcomes. The second half of target 2.5 describes drivers (enabling conditions) leading the way towards these outcomes. The remainder of the targets is less specific on the operational pathway with regards to drivers, activities and outcomes. According to a food systems approach measures of drivers such as investments a) must be explicitly linked to changes in food systems governance or management and b) should translate into measures of impact on food system activities (Reyers et al., 2013). The majority of targets in Appendix 1 does not meet these requirements and needs to be disentangled in more detail during the on-going discussions on means of implementation by member states.

For this purpose, the framework proposed in this paper enables the deconstruction and appraisal of aggregated policy targets into sets of indicators to evaluate progress. This is necessary for the design of effective policy and management actions as well as related monitoring and evaluation programs in real and location-specific food systems as shown by Reyers et al., (2013) for the case of maintenance of ecosystems.

How to develop a theory of transformation

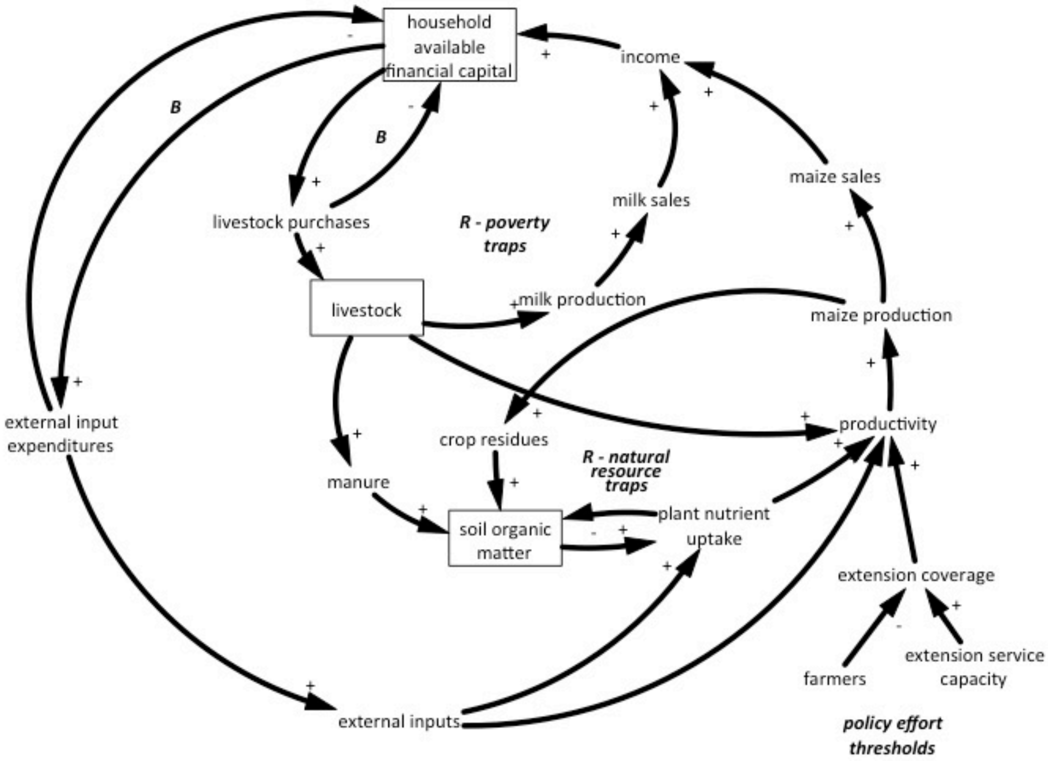
The design, management, and control of complex adaptive systems such as food systems involves a challenging array of distributed and interacting agents, powerful feedback loops, large time delays, and counterintuitive system behaviour. Learning in complex dynamic systems such as food systems is typically slow and hampered by the difficulty to assess the dynamic impact of policy and management actions (e.g., Moxnes, 2004; Sterman, 2008). Innovative methodological strategies such as modelling techniques drawn from complexity science help overcome these difficulties and to design case-specific policy and management actions as well as monitoring and evaluation systems. Of particular interest for a systems approach to food and nutrition security are dynamic simulation models based on system dynamics or agent-based modelling. Dynamic simulation models can serve as tools to explore the interactions of food system elements and assess the multidimensional impact of policy and management actions over time (Hammond & Dubé, 2012).

When implementing the second SDG at local, national and global levels, situations will inevitably arise where there are trade-offs between different targets. 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 dynamic simulation 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 development options are achievable. Such models also allow identifying the most important research needs and designing experiments and studies that fill these needs.

The literature describes a growing number of dynamic simulation models that can be used for this purpose. Existing models can be adjusted to location- and case-specific realities and insights from past modelling applications can be transferred to new ones. Turner et al. (2016) provide a recent review of system dynamics models for studying agricultural and natural resource management issues. This literature review identifies a series of archetypal structures that can be applied to different food systems across scales and levels.

Figure 2 shows generic feedback structures present in several existing system dynamics models on bio-economic processes driving food security and environmental outcomes in small-scale farming systems in Africa. A series of reinforcing feedback loops represent the poverty and resource traps that can restrain transformations towards food and nutrition security and sustainable agriculture. Already at this high level of aggregation, a few dynamic insights are possible. Investments in agricultural productivity, for example, if high enough and in place for long enough, might be effective in reverting poverty traps, i.e., the reinforcing mechanisms that link the accumulation of financial assets with agricultural production (livestock and maize production in this specific example). The same improvements in agricultural productivity might, however, not be effective to break a natural resource trap. This might be the case when higher yielding crop varieties, used in isolation, deplete nutrient stocks even further and thus reinforce the vicious cycle inherent in natural resource traps. One additional barrier to transformation is represented through the mechanism labelled “policy effort threshold”. The policy effort threshold describes preconditions for successful policy and management actions. In the specific case of the example shown in Figure 2, such a threshold exists for all policies that aim at strengthening agricultural extension services to revert the poverty and resource traps. If investment in extension services does not at least grow at the same rate as the farming population grows, extension coverage drops and might push farmers back into one or both of the traps.

Figure 2: Generic structures representing the stocks and feedback loops that determine the dynamic behaviour of natural resource and poverty traps (based on e.g., Stephens et al., 2012; Gerber, 2016; Kopainsky & Nicholson, 2015).



Notes: Rectangles represent stocks. Arrows connecting two variables represent causal links. A causal link indicates both the direction of causality—that a change in the variable at the tail of the arrow causes a change in the variable at the head of the arrow—and whether the two variables change in the same (+) or opposite (−) direction (Stave & Kopainsky, 2015). A circular chain of causal relationships builds a feedback loop that is labeled with its polarity R (indicating self-reinforcing behavior) or B (indicating balancing behavior) (Gerber, 2016) and described in ***bold, italic*** words.

The most important contribution that system dynamics modelling efforts made in the reviewed case studies in Turner et al. (2016) was that they repeatedly identified trade-offs between short-term and long-term policy and management actions (see also Gerber, 2016). The strong tendency of decision makers and stakeholders to rely on short-term solutions gives rise to delayed and unintended consequences and emphasizes the need for longer-term thinking and policy and management actions aimed at fundamental solutions to effectively facilitate transformation of food systems.

One important feature of such fundamental solutions is that they exceed policy effort thresholds (Gerber, under revision). Specifically, this means that policy and management actions not only need to capitalize on leverage points in a food system but also that enough resources are allocated to these actions so that they can have a lasting impact. As long as population grows exponentially, for example, one-time increases in investment in research, extension services or technology development will not be very effective. Instead, they might also have negative consequences in the long run because they generate an experience of policy failure and thus distrust among small-scale food producers (e.g., Kopainsky et al., 2012).

Typically, system dynamics models are used for explaining observed behaviour, building theory and identifying the impact of policy and management actions. The importance of stakeholder engagement in sustainability transitions, however, requires more participatory approaches to modelling. If a system dynamics modelling process is implemented in group settings (e.g., Hovmand, 2014; Kopainsky et al., under review; McRoberts et al., 2013), the objectives of the process expand beyond the construction of a running simulation model. In this case, the modelling process also accommodates goals such as the creation of a shared language, consensus and alignment, as well as commitment (Rouwette & Vennix, 2006). This is not only the case for participatory system dynamics but for participatory modeling in social-ecological systems research in general (Davies et al., 2015). Creation of a shared language, consensus and alignment are of particular importance because differences in stakeholder perspectives and priorities lead to widely differing proposed policy and management actions (Schmitt Olabisi, 2010).

Specifically, the existing body of knowledge from system dynamics and other systems modelling approaches can make the following contributions to the development of theories of change required for successful sustainability transitions in food systems:

- Existing simulation models that can be calibrated to location- and case-specific food systems and used for identifying leverage points as well as slow moving processes that require particularly careful monitoring (cf. review in Turner et al., 2016).
- Structure and building blocks from existing models that seem to be fairly generic across food systems at different scales and levels and that can be used as building blocks and templates for specific applications.
- Structural thinking tools such as system diagrams that can be used for qualitative conceptualization of theories of change (e.g., Brzezina et al., 2016; Stave & Kopainsky, 2015).
- Scripts and guidelines for involving stakeholders in the modelling process at each step of the process (e.g., Hovmand et al., 2012) and for anchoring simulation models in on-going community development processes (Hovmand, 2014).

How to formulate indicators that adequately control for dynamic complexity

Dynamic simulation models help identifying those feedback processes that lead to undesired or unanticipated behaviour and the leverage points for facilitating sustainability transitions in food systems. Controlling for undesired developments and ensuring progress towards targets and goals requires monitoring the central accumulation processes in a food system or the central stocks with their respective in- and outflows. In a case where fully calibrated simulation models are available, those models can be used to quantify critical threshold values for stocks that change the direction and dominance of feedback loops (e.g., by turning a reinforcing feedback loop from working as a virtuous to working as a vicious cycle). In the absence of quantitative simulation models, system diagrams and the archetypes represented therein still allow for the identification of those stocks for which monitoring is most crucial.

The mass balance involved in stocks and flows indicates that the value of a stock increases if the inflow over a certain time period is higher than the outflow over the same period and that the value of a stock decreases if the outflow exceeds the inflow. When transferred to the case of food systems (cf. Figure 2), these principles, for example, imply the following:

- SDG target 2.3 is about the incomes of small-scale food producers. Income is a flow that accumulates into a stock of financial capital, which can subsequently be spent or invested in various ways. Expenditures and investments constitute the outflows of this financial capital stock. Investments, in turn, allow accumulating assets of physical and human capital, which might allow small-scale food producers to break out of poverty and resource degradation traps. If we assume that the target of increasing small-scale food producers' income serves the purpose of enabling small-scale food producers to be able to spend and invest more, then information about the flow of income is not sufficient. Instead, additional information on either the accumulation of financial capital or on expenditures and investments is necessary.
- The same is true for targets about production (target 2.4) and hunger (target 2.1). Production is a flow that needs to be complemented with information on food access and consumption patterns. Comparing what is available and accessible for consumption with what is desired for consumption simultaneously provides information for a hunger target and a food provision target and thus points at important interlinkages between targets.
- A first insight from a systems modelling perspective is thus that if a target concerns a flow, then it is important to complement it with information on the corresponding stock and its outflows. Otherwise it is difficult to assess whether a specific rate of flow is sufficient for achieving progress. The most powerful example for this principle comes from the discussion about mitigation of climate change. Sterman (2008) shows the difficulties that people have in understanding that emission reductions are not sufficient for slowing and eventually halting climate change. Emissions of greenhouse gases are an inflow to the stock of CO_2 in the atmosphere. This stock only stops increasing if the inflow (i.e., the rate of emissions) falls below the outflow from the stock (i.e., the rate of absorption of greenhouse gases from the atmosphere).
- Similarly, if a target concerns a stock, then it is difficult to make inferences on the development of the stock level over time based on information about some but not all of its in- and outflows in isolation.
- Target 2.4 about land and soil quality, for example, concerns the progressive improvement of land and soil quality. Land and soil quality are natural resources. The condition of these resources cannot be improved or even restored simply by decreasing their utilization rate. The condition of the resource is a stock that only increases if the inflow (regeneration) exceeds the outflow (utilization/degradation). Restoring stocks to a desired value that is higher than the current value requires a period of time during which the inflow exceeds the outflow (e.g., Moxnes, 2004). A reduction in the outflow thus needs to be sufficiently big to decrease below the inflow. Measures of land or soil quality thus would have to be complemented by information about the rates of change in land or soil quality.

Conclusions

The objective of this paper was to propose a framework for dealing with the complexity of sustainable food systems in order to support the implementation of the second Sustainable Development Goal "End huger, achieve food security and improved nutrition and promote sustainable agriculture". For this purpose, we combined the integrative perspective underlying the food systems approach with systems analysis and modelling techniques that help unravel and represent the complexity of food systems. The strength of the food systems approach resides in its ability to measure food system outcomes by integrating them together with food system activities and drivers in a linked iterative feedback cycle. Consequently, it provides both a theoretical and a practical set of instruments to conceptualize and understand complex food systems. In turn, a feedback perspective on food systems for the formulation of targets and indicators in the post-2015 development agenda emphasizes the importance of including stocks and flows in the design of monitoring and evaluation frameworks and of using computer simulation modelling for the formulation of implementation plans in location- and case-specific food systems.

The biggest remaining challenge for establishing and implementing location- and case-specific development agendas is the formulation of a clear theory of transformation that does not only include the above-mentioned parts of the framework but also adds aspects of political agency and power relations to the picture. Stakeholders' leverage varies according to hierarchies and scale as well as to representation (Geels, 2011; Jørgensen, 2012). Therefore, a theory of transformation must reveal how leverage is to be treated in the context of food systems. Besides stakeholders' leverage in relation to each other there are also varying levels of influence over changing structures that stakeholders can exercise within a given political environment. Given the diversity of political systems and ways of influence stakeholders have within these systems, the development of a theory of transformation must include stakeholder engagement and learning. These aspects are crucial in a process that is both complex and value-laden and has more than one solution.

Detailed, parameter-rich simulation models that represent the complex cross-scale and cross-level dynamics of food systems are often difficult to develop and calibrate. It is thus important to embed models in a wider assessment process that combines the use of quantitative and qualitative approaches in a way that integrates knowledge from various disciplines and various stakeholder groups in society (Engle et al., 2013; Ericksen et al., 2009; Gómez et al., 2011; Graef et al., 2014; Hammond & Dubé, 2012; Janssen & Anderies, 2013; Ostrom, 2009). In this context, an important avenue of further research in the short run is to distil and synthesize more generic structures and building blocks from existing quantitative simulation models so that these structures and building blocks can be used in varying combinations in new settings.

The above considerations emphasize the importance of comprehending targets as part of a system where indicators need to be monitored comprehensively, including slow moving processes because these processes often cause management problems in complex dynamic systems (e.g., Berkes et al., 2003; Reynolds et al., 2007). Only through a systematic and thorough monitoring process can early warning signals for overshooting threshold values be detected (Rockström et al. 2009). This necessarily requires rich and hierarchical indicator systems that monitor not only goal achievement at large but also offer operational information on leveraging the theory of transformation for a location- and case-specific food system.

Building monitoring systems that not only allow tracking progress towards SDGs but also function as early warning systems require complementary strategies, such as investments in globally harmonized real-time data collecting and reporting systems for SDGs, alongside institutions that foster learning and allow rapid feedback to decision-makers. Such systems can provide the capacity to shift implementation pathways when progress is off track or data indicate that certain systems are approaching thresholds (Norström et al., 2014). These considerations reaffirm that if the SDGs are to overcome the most important shortcomings of the MDGs, it is vital that they consider food systems in their entire complexity. Failure to do so would be a missed opportunity to move beyond outcomes and address the existing complexities in an honest, well-established and effective manner.

References

Akram-Lodhi, A. H. (2013). *Hungry for Change: Farmers, Food Justice and the Agrarian Question*. Halifax, Canada: Fernwood Publishing.

Arango, S., & Moxnes, E. (2012). Commodity cycles, a function of market complexity? Extending the cobweb experiment. *Journal of Economic Behavior & Organization, 84*(1), 321-334. doi: http://dx.doi.org/10.1016/j.jebo.2012.04.002

Avelino, F., & Wittmayer, J. M. (2015). Shifting power relations in sustainability transitions: A multi-actor perspective. *Journal of Environmental Policy & Planning*, 1-22. doi: 10.1080/1523908X.2015.1112259

Berkes, F., Colding, J., & Folke, C. (2003). *Navigating Social-Ecological Systems. Building Resilience for Complexity and Change*. New York, NY: Cambridge University Press.

Bollen, J., Hers, S., & van der Zwaan, B. (2010). An integrated assessment of climate change, air pollution, and energy security policy. *Energy Policy, 38*(8), 4021-4030. doi: http://dx.doi.org/10.1016/j.enpol.2010.03.026

Brzezina, N., Kopainsky, B., & Mathijs, E. (2016). Can organic farming reduce vulnerabilities and enhance the resilience of the European food system? A critical assessment using system dynamics structural thinking tools. *Sustainability, 8*(10), 971. doi: 10.3390/su8100971

Carpenter, S. R., Mooney, H. A., Agard, J., Capistrano, D., DeFries, R. S., Diaz, S., . . . Whyte, A. (2009). Science for managing ecosystem services: Beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences of the United States of America, 106*(5), 1305-1312. doi: 10.1073/pnas.0808772106

Cash, D. W., Adger, W. N., Berkes, F., Garden, P., Lebel, L., Olsson, P., . . . Young, O. (2006). Scale and cross-scale dynamics: Governance and information in a multilevel world. *Ecology and Society, 11*(2 C7 - 8).

Davies, K. K., Fisher, K. T., Dickson, M. E., Thrush, S. F., & Le Heron, R. (2015). Improving ecosystem service frameworks to address wicked problems. *Ecology and Society, 20*(2). doi: 10.5751/ES-07581-200237

Davis, S. J., Peters, G. P., & Caldeira, K. (2011). The supply chain of CO2 emissions. *Proceedings of the National Academy of Sciences, 108*(45), 18554-18559. doi: 10.1073/pnas.1107409108

Economic and Social Council. (2015). Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators: United Nations.

Ericksen, P. J. (2008). Conceptualizing food systems for global environmental change research. *Global Environmental Change, 18*(1), 234-245.

FAO. (2008). *Climate Change and Food Security: A Framework Document*. Rome: Food and Agriculture Organization of the United Nations (FAO).

Foran, T., Butler, J. R. A., Williams, L. J., Wanjura, W. J., Hall, A., Carter, L., & Carberry, P. S. (2014). Taking complexity in food systems seriously: An interdisciplinary analysis. *World Development, 61*(0), 85-101. doi: http://dx.doi.org/10.1016/j.worlddev.2014.03.023

Garnett, T., Appleby, M. C., Balmford, A., Bateman, I. J., Benton, T. G., Bloomer, P., . . . Godfray, H. C. J. (2013). Sustainable intensification in agriculture: Premises and policies. *Science, 341*(6141), 33-34. doi: 10.1126/science.1234485

Garnett, T., & Godfray, H. C. J. (2012). Sustainable Intensification in Agriculture. Navigating a Course through Competing Food System Priorities. A Report on a Workshop. Oxford, United Kingdom: Food Climate Research Network, Oxford Martin Programme on the Future of Food, University of Oxford.

Geels, F. W. (2011). The multi-level perspective on sustainability transitions: Responses to seven criticisms. *Environmental Innovation and Societal Transitions, 1*(1), 24-40. doi: http://dx.doi.org/10.1016/j.eist.2011.02.002

Gerber, A. (2016). Short-term success versus long-term failure: A simulation-based approach for understanding the potential of Zambia's fertilizer subsidy program in enhancing maize availability. *Sustainability, 8*(10), 1036.

Gerber, A. (under revision). Why do food availability policies fail? A simulation approach to understanding food production systems in south-east Africa. *Systems Research and Behavioral Science*.

Griggs, D., Stafford-Smith, M., Gaffney, O., Rockström, J., Ohman, M. C., Shyamsundar, P., . . . Noble, I. (2013). Policy: Sustainable development goals for people and planet. *Nature, 495*(7441), 305-307. doi: http://www.nature.com/nature/journal/v495/n7441/abs/495305a.html - supplementary-information

Hammond, R. A., & Dubé, L. (2012). A systems science perspective and transdisciplinary models for food and nutrition security. *Proceedings of the National Academy of Sciences, 109*(31), 12356-12363. doi: 10.1073/pnas.0913003109

Hovmand, P. S. (2014). *Community Based System Dynamics*. New York, Heidelberg, Dordrecht, London: Springer.

Hovmand, P. S., Andersen, D. F., Rouwette, E. A. J. A., Richardson, G. P., Rux, K., & Calhoun, A. (2012). Group model-building 'Scripts' as a collaborative planning tool. *Systems Research and Behavioral Science, 29*(2), 179-193. doi: 10.1002/sres.2105

Ingram, J. S. I., Ericksen, P. J., & Liverman, D. (Eds.). (2010). *Food Security and Global Environmental Change*. London & Washington DC: Earthscan.

Jørgensen, U. (2012). Mapping and navigating transitions—The multi-level perspective compared with arenas of development. *Research Policy, 41*(6), 996-1010. doi: http://dx.doi.org/10.1016/j.respol.2012.03.001

Kok, K., & Veldkamp, T. (2011). Scale and governance: Conceptual considerations and practical implications. *Ecology and Society, 16*(2 C7 - 23).

Kopainsky, B., Hager, G., Herrera, H., & Nyanga, P. (under review). Transforming food systems at local levels: using participatory system dynamics in an interactive manner to refine small-scale farmers' mental models.

Kopainsky, B., & Nicholson, C. F. (2015, July 19 - 23). *System dynamics and sustainable intensification of food systems: Complementarities and challenges.* Paper presented at the 33rd International Conference of the System Dynamics Society, Cambridge, MA.

Kopainsky, B., Tröger, K., Derwisch, S., & Ulli-Beer, S. (2012). Designing sustainable food security policies in sub-Saharan African countries: How social dynamics over-ride utility evaluations for good and bad. *Systems Research and Behavioral Science, 29*(6), 575-589. doi: 10.1002/sres.2140

Lenzen, M., Moran, D., Kanemoto, K., Foran, B., Lobefaro, L., & Geschke, A. (2012). International trade drives biodiversity threats in developing nations. [10.1038/nature11145]. *Nature, 486*(7401), 109-112. doi: http://www.nature.com/nature/journal/v486/n7401/abs/nature11145.html - supplementary-information

Liu, J., Dietz, T., Carpenter, S. R., Alberti, M., Folke, C., Moran, E., . . . Taylor, W. W. (2007). Complexity of coupled human and natural systems. *Science, 317*(5844), 1513-1516. doi: 10.1126/science.1144004

Marenya, P. P., & Barrett, C. B. (2009). Soil quality and fertilizer use rates among smallholder farmers in western Kenya. *Agricultural Economics, 40*(5), 561-572. doi: 10.1111/j.1574-0862.2009.00398.x

McRoberts, K. C., Nicholson, C. F., Blake, R. W., Tucker, T. W., & Díaz Padilla, G. (2013). Group model building to assess rural dairy cooperative feasibility in South-Central Mexico. *International Food and Agribusiness Management Review, 16*(3), 55-98.

MEA. (2005). *Millennium Ecosystem Assessment, Ecosystems and Human Well-being: Synthesis*: Island Press, Washington, D.C.

Moxnes, E. (2004). Misperceptions of basic dynamics: the case of renewable resource management. *System Dynamics Review, 20*(2), 139-162.

Neufeldt, H., Jahn, M., Campbell, B. M., Beddington, J. R., DeClerck, F., De Pinto, A., . . . Zougmoré, R. (2013). Beyond climate-smart agriculture: Toward safe operating spaces for global food systems. *Agriculture & Food Security, 2*(13). doi: doi:10.1186/2048-7010-2-12

Norström, A. V., Dannenberg, A., McCarney, G., Milkoreit, M., Diekert, F., Engström, G., . . . Sjöstedt, M. (2014). Three necessary conditions for establishing effective Sustainable Development Goals in the Anthropocene. *Ecology and Society, 19*(3). doi: 10.5751/ES-06602-190308

Ostrom, E. (2009). A general framework for analyzing sustainability of social-ecological systems. *Science, 325*(5939), 419-422. doi: 10.1126/science.1172133

Parris, T. M., & Kates, R. W. (2003). Characterizing a sustainability transition: Goals, targets, trends, and driving forces. *Proceedings of the National Academy of Sciences, 100*(14), 8068-8073. doi: 10.1073/pnas.1231336100

Perrings, C. (1989). An optimal path to extinction?: Poverty and resource degradation in the open agrarian economy. *Journal of Development Economics, 30*(1), 1-24. doi: http://dx.doi.org/10.1016/0304-3878(89)90048-5

Reyers, B., Biggs, R., Cumming, G. S., Elmqvist, T., Hejnowicz, A. P., & Polasky, S. (2013). Getting the measure of ecosystem services: a social–ecological approach. *Frontiers in Ecology and the Environment, 11*(5), 268-273. doi: 10.1890/120144

Reynolds, J. F., Smith, D. M. S., Lambin, E. F., Turner, B. L., Mortimore, M., Batterbury, S. P. J., . . . Walker, B. (2007). Global desertification: Building a science for dryland development. *Science, 316*(5826), 847-851. doi: 10.1126/science.1131634

Richardson, G. P., & Pugh, A. (1981). *Introduction to System Dynamics Modeling*. Williston, VT; Waltham, MA: Pegasus Communications.

Rockström, J., Steffen, W., Noone, K., Persson, A., Chapin, F. S., Lambin, E. F., . . . Foley, J. A. (2009). A safe operating space for humanity. *Nature, 461*(7263), 472-475.

Rouwette, E. A. J. A., & Vennix, J. A. M. (2006). System dynamics and organizational interventions. *Systems Research and Behavioral Science, 23*(4), 451-466. doi: 10.1002/sres.772

Saysel, A. K. (2014, July 20 - 24). *Analyzing soil nitrogen management with dynamic simulation experiments.* Paper presented at the 32nd International Conference of the System Dynamics Society, Delft, The Netherlands.

Schmitt Olabisi, L. K. (2010). The system dynamics of forest cover in the developing world: Researcher versus community perspectives. *Sustainability, 2*(6), 1523-1535.

Stave, K. A., & Kopainsky, B. (2015). A system dynamics approach for examining mechanisms and pathways of food supply vulnerability. *Journal of Environmental Studies and Sciences, 5*(3), 321-336. doi: 10.1007/s13412-015-0289-x

Stephens, E. C., Nicholson, C. F., Brown, D. R., Parsons, D., Barrett, C. B., Lehmann, J., . . . Riha, S. J. (2012). Modeling the impact of natural resource-based poverty traps on food security in Kenya: The Crops, Livestock and Soils in Smallholder Economic Systems (CLASSES) model. *Food Security, 4*(3), 423-439. doi: 10.1007/s12571-012-0176-1

Sterman, J. D. (1989a). Misperceptions of feedback in dynamic decision making. *Organizational Behavior and Human Decision Processes, 43*(3), 301-335.

Sterman, J. D. (1989b). Modeling managerial behavior: Misperceptions of feedback in a dynamic decision making experiment. *Management Science, 35*(3), 321-339.

Sterman, J. D. (2000). *Business dynamics. Systems thinking and modeling for a complex world*. Boston et. al.: Irwin McGraw-Hill.

Sterman, J. D. (2008). Risk communication on climate: Mental models and mass balance. *Science, 322*, 532-533.

Turner, B., Menendez, H., Gates, R., Tedeschi, L., & Atzori, A. (2016). System dynamics modeling for agricultural and natural resource management issues: Review of some past cases and forecasting future roles. *Resources, 5*(4), 40.

United Nations. (2016). The Sustainable Development Goals Report 2016. New York, NY: United Nations.

Appendix

Appendix 1: Targets for a sustainable development goal on ending hunger, achieving food security and improved nutrition and promoting sustainable agriculture

Goal 2: End hunger, achieve food security and improved nutrition and promote sustainable agriculture

Targets

2.1 By 2030, end hunger and ensure access by all people, in particular the poor and people in vulnerable situations, including infants, to safe, nutritious and sufficient food all year round

2.2 By 2030, end all forms of malnutrition, including achieving, by 2025, the internationally agreed targets on stunting and wasting in children under 5 years of age, and address the nutritional needs of adolescent girls, pregnant and lactating women and older persons

2.3 By 2030, double the agricultural productivity and incomes of small-scale food producers, in particular women, indigenous peoples, family farmers, pastoralists and fishers, including through secure and equal access to land, other productive resources and inputs, knowledge, financial services, markets and opportunities for value addition and non-farm employment

2.4 By 2030, ensure sustainable food production systems and implement resilient agricultural practices that increase productivity and production, that help maintain ecosystems, that strengthen capacity for adaptation to climate change, extreme weather, drought, flooding and other disasters and that progressively improve land and soil quality

2.5 By 2020, maintain the genetic diversity of seeds, cultivated plants and farmed and domesticated animals and their related wild species, including through soundly managed and diversified seed and plant banks at the national, regional and international levels, and promote access to and fair and equitable sharing of benefits arising from the utilization of genetic resources and associated traditional knowledge, as internationally agreed

2.a Increase investment, including through enhanced international cooperation, in rural infrastructure, agricultural research and extension services, technology development and plant and livestock gene banks in order to enhance agricultural productive capacity in developing countries, in particular least developed countries

2.b Correct and prevent trade restrictions and distortions in world agricultural markets, including through the parallel elimination of all forms of agricultural export subsidies and all export measures with equivalent effect, in accordance with the mandate of the Doha Development Round

2.c Adopt measures to ensure the proper functioning of food commodity markets and their derivatives and facilitate timely access to market information, including on food reserves, in order to help limit extreme food price volatility