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Transforming food systems at local levels: using participatory system dynamics in an interactive manner to refine small-scale farmers' mental models

Birgit Kopainsky[1*], Gerid Hager[1], Hugo Herrera[1,2], Progress H. Nyanga[3]

[1] System Dynamics Group, Department of Geography, University of Bergen, Postbox 7800, 5020 Bergen, Norway
[2] Department of European Studies, University of Palermo, Via Ugo Antonio Amico 3, 90100 Palermo, Italy
[3] Geography and Environmental Studies Department, School of Natural Sciences, University of Zambia, P.O. Box 32379, Lusaka, Zambia, 10101

* Corresponding author
System Dynamics Group, Department of Geography, University of Bergen, Postbox 7800, 5020 Bergen, Norway
e-mail: birgit.kopainsky@geog.uib.no; phone: +47 55 58 30 92; fax: +47 55 58 30 99

E-mail addresses
Gerid Hager: geridhager@gmail.com
Hugo Herrera: hugojhdl@gmail.com
Progress H. Nyanga: pnyanga@yahoo.co.uk

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Conflicts of interest

The authors declare no conflict of interest.

Abstract

Food systems will need to undergo considerable transformation. To be better prepared for and resilient to uncertainty and disturbances in the future, resource users and managers need to further develop knowledge about the food and farming system, with its dominating feedback structures and complexities, and to test robust and integrated system-based solutions. This paper investigates how participatory system dynamics modeling can be adapted to groups at the community level with low or no formal educational background. The paper also analyses the refinement of workshop participants' mental models as a consequence of a participatory system dynamics intervention. For this purpose, we ran two workshops with small-scale farmers in Zambia. Analysis of workshop data and post-workshop interviews shows that participatory system dynamics is well adaptable to support an audience-specific learning-by-doing approach. The use of pictures, objects and water glasses in combination with the basic aspects of causal loop diagramming makes for a well-balanced toolbox. Participants acquire understanding that is also relevant beyond systems thinking in that it offers a range of practical insights such as a critical evaluation of common food security strategies.

Keywords

adaptation; mental model refinement; food systems; knowledge management participatory modeling; system dynamics; systems thinking

1 Introduction

Food systems will need to undergo significant transformation and adaptation in order to meet future challenges of achieving food security for all, decreasing environmental impacts and adapting to climate change (Foley et al., 2005, Godfray et al., 2010; Godfray et al., 2011). Food systems are social-ecological systems (SES) that consist of biophysical and social factors linked through feedback mechanisms (Berkes et al., 2003). These mechanisms determine the outcome of food systems over time. A wide range of policy and management actions is available to create positive outcomes at the micro-level in the face of the above-mentioned challenges. For the case of small-scale farmers in sub Saharan Africa, these actions include direct interventions in farm management practices, adoption of new technologies and knowledge management, incl. strengthening networks and local governance (Below et al., 2010). As SES are both complex and adaptive, they require resource users and mangers to continuously test and develop new knowledge and understanding in order to cope with change and uncertainty (e.g., Carpenter & Gunderson, 2001, Thompson & Scoones, 2009, Darnhofer et al., 2010). This reinforces the need for effective knowledge management.

Participatory modeling (e.g., Voinov & Gaddis, 2008; Voinov & Bousquet, 2010) is often used in the context of knowledge management because it facilitates inclusion of diverse knowledge sets and at the same time enables explicit examination of the trade-offs and synergies in different food system outcomes under alternative management scenarios. Davies et al. (2015) explored the efficacy of different participatory modeling approaches with respect to their ability to contribute to knowledge management, that is, to generate four important elements of social capital needed to address wicked or complex dynamic problems: enhancing social learning and capacity building; increasing transparency; mediating power; and building trust. Their study found that mediated modeling or participatory system dynamics, group mapping, and mental/conceptual modeling are all likely to generate elements of social capital that can improve ecosystem services or social-ecological systems frameworks.

The field of System Dynamics (SD) has a long tradition of facilitating learning about complex systems through the use of system diagrams and computer simulation models (Lane, 1992, Vennix, 1996, Sterman, 2000), also in the context of agricultural production and development (e.g., Matinzadeh et al., 2017; Walters et al., 2016). It utilizes those tools to develop an understanding of the interdependent structures of dynamic systems, that is, the ability to: understand how the behavior of a system arises from the interaction of its agents over time (i.e., dynamic complexity); discover and represent feedback processes (both reinforcing and balancing) hypothesized to underlie observed patterns of system behavior; identify stock and flow relationships; recognize delays and understand their impact; identify nonlinearities; and recognize and challenge the boundaries of mental (and formal) models (Booth Sweeney & Sterman, 2000).

Participatory system dynamics employs the use of system diagrams (Videira et al., 2014) and computer simulation models (Andersen et al., 2007) in group-settings. While the purpose of

participatory SD is often the construction of a running simulation model, the process accommodates a range of additional goals: mental model refinement, commitment, the creation of a shared language, consensus and alignment (Rouwette & Vennix, 2006). The effectiveness of participatory SD, however, might be restricted in contexts in which computer simulation is not possible or not fit for purpose. Hence, a different approach might be required.

In this paper we report on a participatory SD modeling process tailored to groups at the community level with very basic or no formal educational background using an interactive learning-by-doing approach. This approach unlocks participatory SD and its ability to explicitly examine the direct and indirect consequences of proposed management options to a relatively new audience. Our approach thus acts as a knowledge management strategy that strengthens local communities through shared systems learning, networking and an increased focus on local governance and empowerment.

There is no single classification of knowledge management strategies, but rather a series of theories about how knowledge is created and shared by individuals in the same network (e.g. Berkes, 2008; Maier & Remus, 2003). The term knowledge management strategy is usually used to describe approaches for managing knowledge-related activities such as knowledge elicitation, information dissemination, and learning (Bhatt, 2002). In this paper, we focus on learning, that is, the process of building a common understanding of the main dynamics of a system.

Learning in the context of participatory modeling processes results from participants sharing their own mental-models (tacit knowledge) with the rest of the group (Tavella & Franco, 2015; Choi & Lee, 2002). During this process, mental models are captured in system maps or formal simulation models and thus transformed into explicit knowledge that can be accessed by others (e.g., Sims & Sinclair, 2008). Moreover, knowledge captured in a model in the form of data and causal relationships is used to produce new knowledge about effects and consequences of interventions on the system. Hence, participants not only learn from each other but also from the model itself (Tavella & Franco, 2015) and this new knowledge can then be used to tackle other problems or to broaden the range of options explored to tackle to problem at hand (Berkes, 2008).

The objective of this paper is twofold:

1. It reports on the modification of the participatory SD modeling method so that it can be used as a knowledge management strategy at the community level adaptable to contextual factors, incl. the educational background of the participants.
2. It explores how this adapted design for participatory SD can facilitate participant learning and mental model refinement about food systems and with that support decision making at the local level.

For this purpose, we designed and ran two participatory SD workshops with small-scale farmers in Zambia. Those small-scale farmers face recurrent food insecurity as well as rapidly changing and increasingly volatile framework conditions, which calls for considerably strengthening their adaptive capacities. Video material from the workshops as well as

interviews at two different times after the workshops allowed us to track changes in participants' systemic understanding of their food security and livelihood situation and options they considered for improving it. This data provides clear evidence that the participatory SD intervention effectively helped participants to improve their understanding of the archetype structures that lock them in a vicious circle of food insecurity and poverty. Additionally, the intervention provided participants with tools to evaluate not only the direct and short-term but also the indirect and long-term consequences of different coping and adaptation options.

2 Methods

A participatory SD process is generally broken down into three distinct stages: (1) problem scoping, (2) workshop planning, and (3) the actual participatory modeling workshops (Hovmand, 2014). The problem-scoping phase involves interviews and discussions to identify the problem of interest. The workshop planning phase designs the participatory modeling workshops by developing a series of activities or exercises and facilitated discussions that are eventually implemented in the workshops and evaluated afterwards. This section describes the participatory SD process in two case study villages in Zambia and the subsequent analysis of video and audio data.

2.1 Participatory system dynamics workshops

Site description

According to the Food Security Index (The Economist, 2013), Zambia is one of the ten most food insecure countries in the world. Agricultural productivity in the country is held back by a lack of access to inputs and services, as well as to transport, markets and other social infrastructure. At present, small-scale farmers do not have access to financial services, and even larger enterprises lack access to long-term finance. Soil fertility is decreasing, and agricultural farming systems are one sided. This is particularly the case for small-scale farmers and staple crops, mainly maize production (Neubert et al., 2011). External drivers, such as climate change and economic shocks, are posing increasingly significant challenges to the agricultural sector. Rainfall patterns have changed significantly since the late 1980s and, on average, delayed the onset of the rainy season by one to two months (Neubert, et al., 2011; Nyanga et al., 2011).

This study was conducted in Chibombo district. Chibombo district is located in the Central Province, about 90 km to the north of Lusaka. It is a farming district where about 90% of the district population depends on agriculture for their livelihoods. The district lies within the Agro-Ecological Region II, spanning from east to west covering the central part of Zambia. It receives rainfall between 800 and 1200 mm per year and is characterized by relatively good soil fertility with limitations due to low nutrient retention and water holding capacity (FAO, 1998). Climatic conditions make it suitable for production of most common crops, such as maize, cotton, sunflower, cowpeas, beans, groundnuts, paprika, soya beans, and tobacco, amongst others. Small-scale farmers are responsible for over 75% of crop production in the

district. Commercial agriculture is largely concentrated in the south of the district. The case study villages are located in the north of the district where small-scale agriculture is dominant.

Problem scoping and workshop planning

Our case study work started with problem scoping and workshop planning. We conducted in-depth interviews with 20 small-scale farmers where we focused on their dynamic decision making in the context of food security and livelihoods (Saldarriaga et al., 2014). Using these interviews, we inductively developed first hypotheses about problem issues, such as food availability at the household level as an important dimension of food security, or household budget constraints, and formalized them in a simplified causal loop diagram (CLD). CLDs are conceptual tools in which a chain of cause-and-effect relationships is traced through a set of variables that characterize a dynamic issue (Videira, et al., 2014). The simple CLD used in the workshops represented the main feedback loops driving household food security and was based on more detailed CLDs stemming from the interview analysis from Spicer (2015). Spicer followed and adapted a method proposed by Kim and Andersen (2012), which combines aspects of grounded theory with SD model building. It offers a systematic step-by-step approach that can be used to rigorously code and interpret qualitative data, such as interview transcripts, to create causal maps for SD modeling. To optimize the limited time available for the participatory SD workshops, we decided to build the workshop activities on this CLD, which serves as a conceptual model (Richardson, 2013), rather than starting from scratch.

Figure 1 shows the base CLD used for workshop planning. The CLD links the key stock variables through two major reinforcing feedback loops. Available financial assets (cash), the amount of food produced over the course of a harvesting season (produced food) and the actual food security situation (available food) are at the heart of farmers' concerns. The more cash a household has available, the more inputs (fertilizer, seed, herbicides) they can purchase. More inputs allow farmers to cultivate more land and thus increase the amount of food they produce. Some of this food is sold directly (cash crops) but often it is only sold if there is any surplus between what is produced and what is required to feed the household (represented in the variable available food). The more a household can sell, the more income they generate which adds to the stock of cash. A similar reinforcing feedback loop links livestock to cash (through sales of animal products or animals) and back to livestock (through purchases of additional livestock).

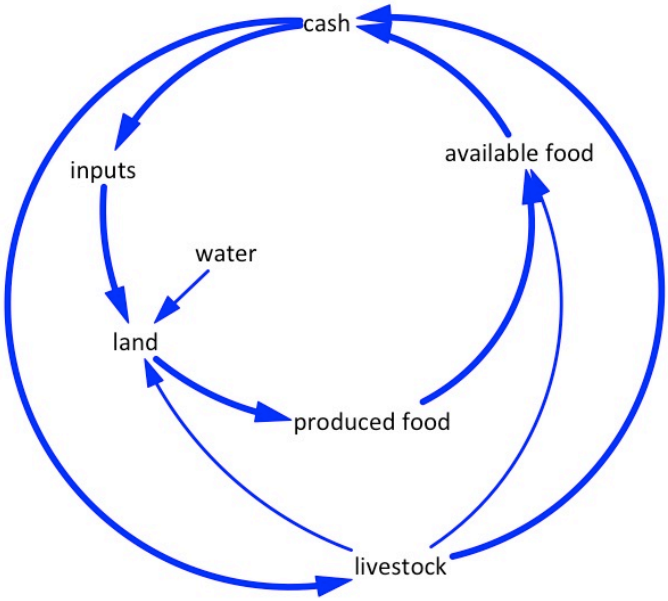

Figure 1: Highly aggregated causal loop diagram distilled from in-depth interviews with farmers. The diagram shows the main reinforcing feedback loops responsible for livelihoods (represented by the variable „cash") and food security (represented by the variable „available food").

We planned on building a similar CLD with workshop participants and to use the CLD to discuss a) mechanisms that cause food insecurity to persist over time, b) stressors to the system and c) options that are available to farmers for improving food system outcomes. The objective of the workshops was thus not to formulate and implement policy and management actions. This is part of subsequent steps in a participatory modeling process. Instead, our purpose was to improve the community understanding of the problem and the key relationships in the system by discussing the archetype structure outlined in the CLD.

To achieve our objectives, we tailored the participatory SD modeling and simulation process to contextual considerations such as limited time available (max. 3 hours) as well as participants' relatively low formal education levels and familiarity with learning processes that use conceptual and abstracted frameworks for analysis. The average years of schooling was around 2-3 years and some of the participants were unable to read. In this context, our assumption was that conventional SD computer simulations, represented in behavior over time graphs, might be confusing, ineffective and a rather meaningless tool to support a better understanding of the system structure and its dynamic implications. This assumption is also linked to research showing how people, in this case highly educated university students (from MIT), have great difficulties reading and understanding simulation outputs such as fairly basic stock and flow behavior graphs (Booth Sweeney & Sterman, 2000, Cronin & Gonzales, 2007). Moreover, when working at the local community level, the infrastructure itself (appropriate equipment such as computers, electricity available, etc.) was a major practical constraint to the use of computer simulations. There simply was no electricity available. To adapt to these circumstances, we opted for an experiential, learning-by-doing approach and aimed at unfolding the process of SD modeling and causal loop diagramming intuitively, explaining each step but without explicitly describing any diagram specifics. We used pictures and objects such as bags of harvested maize, hybrid seed or coins to visualize and clarify the concept of variables. We used arrow symbols for links between variables and the resulting loops but did not denote link polarity, nor did we explicitly mark loops as either

reinforcing or balancing. We introduced regular drinking glasses filled with water as analogies for stock levels to tangibly capture desired states, to illustrate the behavior that feedback loops give rise to and to qualitatively simulate anticipated impacts of stressors and options.

Participatory modeling workshop

The participatory modeling workshop consisted of five main phases. One group facilitator, one modeler/reflector and three research assistants acting as process coaches and recorders (Hovmand, 2014) guided the process in the two case study villages. The workshops lasted approximately three hours with 10-15 participants each. In facilitated working groups, such as for learning, problem solving, or decision making, small size (7 to 15 people) is considered optimal, for it preserves individual positioning, but also gives rise to genuine group processes (Phillips & Phillips, 1993).

Phase one included framing and positioning of the problem, collecting important variables and setting system boundaries. During this phase, we discussed the most important aspects of food security and farmers' livelihoods and collected them as variables on the whiteboard via labels (sheets of paper with terms on them). We further conceptualized and distinguished variables by means of pictures and common objects. In phase two, connections between variables needed to be established by drawing links between variables. Phase three focused on defining desired states for the main stock variables and comparing them to perceived states of the real system. We visualized desired states by filling water into glasses. Subsequently, we used levels in water glasses to visualize actual states and reason about the dynamic implications of full or increasing and empty or decreasing glasses on other variables. Stressors that can change stock levels (both in decreasing inflows as well as increasing outflows) and subsequent effects due to feedback loops were addressed in phase four. Phase five concentrated on options for farmers to increase different stock levels and on how options can have multiple effects on the system, some of them unintended.

2.2 Data collection and analysis

Outcomes of participatory SD interventions go beyond the construction of a formal simulation model. In this paper, we focus on the effects of participatory SD on participants' mental models, and specifically on mental model refinement. The term mental model has a long history in the SD literature (Forrester, 1971; Richardson & Pugh, 1981; Richardson et al., 1994; Vennix, 1996; Doyle & Ford, 1999; Kim, 2009; Rouwette et al., 2011; Black & Andersen, 2012; Groesser & Schaffernicht, 2012). In this paper, we use the term mental model to describe a "conceptual representation of a social problem that can be externalized in the form of a causal loop diagram" (Doyle & Ford, 1999: 414).

Several authors have recognized participatory SD as an ingredient of mental model refinement (Richardson, et al., 1994; Vennix, 1996; Akkermans & Vennix, 1997; Richmond, 1993; Maani & Maharaj, 2004; Rouwette, et al., 2011; Black & Andersen, 2012). During the modeling workshops, participants undergo a paradigm shift in their understanding of how the real world works. This allows them to think holistically and recognize connections

between different actions and their effects (Richardson, et al., 1994; Maani & Maharaj, 2004).

Directly evaluating the effect of a participatory SD workshop on participants' mental models and observing its unfolding is, however, not straightforward, and there are many different assessments proposed in the literature. In this paper, we draw on the assessment measures developed by Hopper & Stave, (2008), who differentiate between basic, intermediate and advanced systems thinking levels. For the purpose of our study, we only consider basic and intermediate systems thinking levels. On the basic systems thinking level, skills involve recognizing interconnections, identifying feedback, and understanding dynamic behavior. On the intermediate systems thinking level, skills refer to the ability to differentiate types of variables and flows, and the ability to use conceptual models.

To evaluate to which extent participants changed their understanding of the world and incorporated feedback mechanisms and system thinking into their mental models we draw on videos of the workshops, workshop translations, and transcripts. We further substantiate the results by translated and transcribed interview data collected one week after the workshops. Interviews were conducted with four participants per workshop (eight in total), of which two men and two women. We made sure that one of the men and one of the women had been very active during the workshop and that the other man and women had been fairly inactive during the workshop. The interviews were supported by prints of pictures of the final workshop diagram (Figure 2) as the goal was to better understand if the participants could use the diagram in a meaningful way, and not to plainly test whether they had memorized systems concepts from the workshop. One year after the workshops, we interviewed the same participants again and asked them what they remembered from the workshops as well as what their experiences had been since the workshops, i.e., whether they had changed anything in their decision making relating to food security.

Figure 2: Final diagrams developed in the two workshops. Variables are written out as well as visualized both with pictures and objects. Water glasses are placed on stock variables to illustrate the processes building and depleting stocks and the behavior that feedback loops give rise to.

Given that the participants had no prior training of causal loop diagramming or explicit socio-ecological systems thinking, if some level of mental model refinement and a convergence towards shared understanding has taken place as result of our intervention, we would at least expect to see (1) a participant's ability to handle the diagram and its logic to

recollect and form causal chain and loop arguments as well as make dynamic inferences relating to the contents discussed during the workshop, and (2) a fair amount of overlapping responses from participants.

3 Results

Over the course of the workshops, farmers developed shared knowledge and understanding of their daily farming and food practice in terms of a farming and food system. Concrete, practice-based knowledge was successfully integrated with abstract system concepts. Farmers developed the basic concepts of a dynamic feedback perspective and, on average, achieved an intermediate level of systems thinking. In particular, participants gained understanding of the following SD and systems thinking concepts that we will further substantiate in the sub-sections of this chapter:

- From items (orientation on practice) to variables (organization in categories). Participants became able to abstract items and activities that they use on a daily basis into variables as well as cause-and-effect relationships.
- From separate connections and simple causal links to chains and closed loops. Participants became able to link their activities throughout a farming season and the key decisions they make into closed feedback loops.
- From linear chains of events and simple dynamic descriptions of change to dynamic narratives of closed-loop behavior. In particular, participants developed an explicit understanding of reinforcing feedback and how such loops can work both as vicious as well as virtuous cycles.
- Broadening understanding of different food security options, display of conceptual agency in developing varied understandings through critical judgment and evaluating strategies. Participants started reflecting on unintended consequences and direct as well as indirect effects of proposed food security options.
- From a single strategy solution to a given problem to multiple solutions dependent on specific initial problem conditions. Participants explored different food security options depending on the initial situation on a given farm and developed various scenarios.

For the purpose of illustration, we include the analysis of two workshop phases before presenting results from the post-workshop interviews. We use short sequences (episodes) and an analysis of literal explanations from participants to assess mental model refinement.

3.1 Refinement of mental models during workshops

Phase 1: Defining variables

A critical episode took place during the first phase of both workshops (supplementary information 1). After having collected important variables, it was time to specify the meaning of variables by allocating pictures and objects to the respective variable labels. The

diagram at this stage consisted of the following labels: cash, food produced, food available, inputs, livestock, water and land. Two pictures (rain and animals) had already been successfully placed. The picture for inputs (fertilizer and seed packs), on the other hand, had to be changed from produced food to inputs, in order to fulfill the requirements of categorical allocation. Thus, the diagram fragments already contained information on categorization and a short history of change and repair. Several participants pleaded for putting the picture of fertilizer and seed packs on the land label. This represents a process-oriented use of implements, as land is where implements need to go in farming. Other participants, however, disagreed and employed a more categorical form of interpreting the task. They put the picture of fertilizer and seed packs on the inputs label and explained that the picture represented these inputs. This involved some discussion where the group stated, challenged, tested and finally aligned their understanding under conditions of categorization.

At this point, we may assume that the group had resolved the tension by arriving at a shared understanding and was ready to move on and work on new challenges based on these insights. However, the new understanding was not stabilized and required another very similar round of alignment and repair. This time, it was not a picture of fertilizer and seed but a pack of actual fertilizer that had to be put. In other words, fertilizer now came in a different modality, which seemed to pose a somewhat different challenge. All in all, it took the group a total of 17 placements of pictures and tangible objects to align and stabilize their understanding of conceptual categorization of things highly familiar to them.

Phase 3: Behavior that feedback loops give rise to

Another critical episode in terms of mental model refinement took place in the third phase of the workshops (supplementary information 2). Right before, the participants accepted the water glass analogy and established desired levels for the three main stocks (cash, produced food and available food) by pouring water into the glasses. All glasses were filled to the brim. Hence, they specified their level of desire with “as much as possible” rather than a clear amount. At this point, the diagram resembled a simple qualitative SD model with feedback loops. The task now focused on using the diagram to reason about dynamic implications. However, the facilitator did not mention “dynamics” or “behavior” specifically. To initiate reasoning, the facilitator poured out water from the glass representing the amount of cash available and posed the question: “What if only this remains; then?”

The first proposed explanation to this question in the second workshop remained at the stage of open loop reasoning, where the participant explored multiple connections and cross-impact but no further feedback dynamics. A second participant, together with the facilitator and other members of the group, developed a narrative that employed the same conceptual characteristics but that was more detailed in terms of causal links and also more extensive as the narrative expanded beyond prior explanations. The vicious characteristic of the reinforcing loop developed as a consequence of those detailed and extended explorations. Throughout this episode, the participants managed to stabilize the conceptions of existing loops and causal paths as well as their dynamic implications. This understanding increased their conceptual agency and empowered them to use their new knowledge to actively shape subsequent arguments.

After this episode, the water glass analogy remained a crucial anchoring point for subsequent discussions of stresses to the system and finally, the evaluation of available options to shift loop direction towards a virtuous cycle and to increase accumulation in the respective resource stocks.

3.2 Mental model refinement beyond the workshops

Post-workshop interviews further illustrate mental model refinement. Here, we report separately on interviews conducted one week after the workshops and interviews conducted one year after the workshops.

Interviews one week after the workshops

During the interviews and with the CLD at hand (Figure 2), participants displayed a fairly high degree of convergence on systemic issues and option development to increase food security. They converged on their use of language, on their ability to meaningfully draw connections between crucial variables and identify loops. The participants were able to use the conceptions within the diagram while applying them to different scenarios and situational considerations. Also, the participants extended the discussion of issues beyond the visible while remaining able to reason in a concise, systemic way.

Apart from describing the most important causal chains and reasoning along the loops, participants also extensively reasoned about some specific issues or concentrated on specific aspects within the system. The interview excerpt with female participant 7 in workshop 2 (ii_FP7) illustrates a participant's understanding of how feedback loops work and how different activities or decisions such as purchasing food versus purchasing seed determines whether a reinforcing feedback loop acts as a vicious or virtuous cycle. The participant elaborates on one specific issue – being caught in the poverty trap that threatens food security and limits one's prospects for progress. According to her, one needs to have enough food to sustain oneself and enough cash to re-start the production process. From there, slow progression is possible. If one has only food but no cash or cash but no food, starting the production loop seems infeasible. Food is sold for cash worsening food insecurity. Cash is used to buy food, which undermines the purchase of seed. Also, her description holds the notion of accumulation as a process over time:

- *ii_FP7: Because you can have food but if you don't have cash it's a problem, because you start selling the food to solve other problems. … That's where I want to talk about when you farm here (production loop) it will help you to avoid buying food, because when you start buying food it means that the glass for cash will reduce. So it is better when you find cash you buy seed or fertilizer than buying food, and like that you can improve a bit.*
- *Male interviewer: Okay, so meaning you have improved a bit as well on the glass (cash)?*
- *ii_FP7: Yes but this glass (cash) does not just get full at once. You just do it bit by bit, so it does not get full at once. …Most of the time, you can be having cash and you can*

> *just be buying food. Hence cash cannot manage to reach here (production) and like that you cannot fill in the glass (cash).*

In another exchange with the male interviewer (MI), the issue was explored further, leading to the elaboration of an aspect that further reinforces the vicious cycle. If one has no money to buy certified seed, recycled seed is used, which in turn leads to a decrease in production, consequently worsening food security and prospects for selling produced food at the same time. Also the topic of piecework (laboring work) is explored in comparison with food production as a means for income:

- *MI: Now where does that little money come from? Because we want to know the source of the little money, is it from piecework, maize or what?*
- *ii_FP7: Sometimes it comes from piecework.*
- *MI: Okay.*
- *ii_FP7: When you find that little money before you reach this side (production) … because when you find cash and it's little, such that you cannot reach here (inputs), it will not be possible for you to buy inputs because you used that little money to buy food, then you will be forced to use the recycled seed for planting. Hence, you will have less produced food.*

Above all, the interviews show the participants' ability to make active, deliberate use of the CLD at hand, which reflects their understanding of some of the archetype structures underlying the dynamic of the system. This evidence suggests participants have incorporated a systemic way of thinking of the problem into their refined mental models and that participants can recognize feedback loop connections between different elements. They verbally recreate and meaningfully embed further understanding of a multi-loop system in a causally consistent manner. And, they actively respond to and frame the conversation in accordance with the interviewer's focus on systemic aspects and options to increase food security and livelihoods.

Interviews one year after the workshops

One year after the workshops, we asked participants what they remembered from the workshops and what their experiences in terms of decision making, food security and livelihoods had been in the meantime. For these interviews, we did not show pictures of the diagrams that had been developed during the workshops. Instead, participants recreated what they remembered from the diagram and the narratives around the diagram. Figure 3 shows diagrams drawn with one participant per workshop. The diagrams illustrate the persistence of participants' understanding of the archetype structures developed during the workshops and some of the diagrams even contain additions by the participants that helped them reflect on the behavior generated by the feedback loops and the impact of various options to improve their food security and livelihood situation.

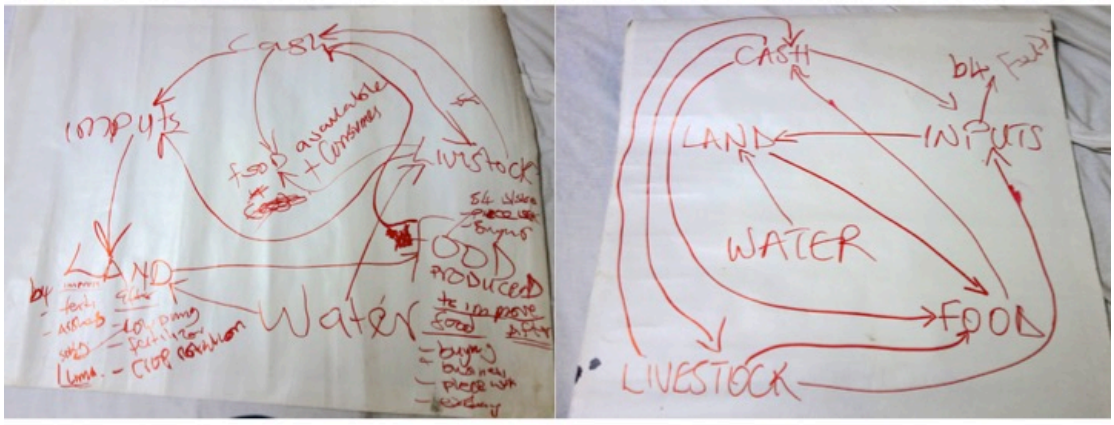

Figure 3: Diagrams drawn with and by one participant of each workshop, one year after the workshops were held. The diagrams contain most if not all of the original variables and links and some participants add more variables that seem to be important for reflecting on how participants' decisions dynamically affect food security and livelihood outcomes.

In several interviews, participants commented on how the diagram had served as an eye opener in the sense that it had helped them see the interconnected nature of the different decisions that they make throughout the year. As a consequence, most of them started budgeting for food and/or money in coordination with their spouse to prevent the reinforcing feedback loop between food and money to act as a vicious cycle.

The water glass metaphor remained a strong analogy after one year. This became obvious every time participants listed options beyond budgeting that they had tried out to "fill the water glasses", such as investments in livestock or in small business. The experiences with implementing these options were mainly positive. However, participants also commented on the delicate balance one needs to strike when investing, because purchasing livestock, for example, can erode the remaining cash level too much or create ongoing pressure on the cash and food stocks due to the running costs related to keeping livestock. All these processes create the danger of turning the reinforcing feedback loops in the system into vicious cycles.

The limits to the diagram and narrative developed throughout the workshops became obvious in discussions with participants that focused on the production of charcoal from cutting wood as an option to increase the available cash. While farmers were aware of the long-term danger and side effects of this option, they saw no other short-term option to set the reinforcing feedback loops in motion. They talked about the need to exit the charcoal strategy after some time to avoid the occurrence of unintended consequences and vicious cycles but remained fairly vague about specifics.

4 Discussion

The system dynamics model at the heart of a participatory modeling process (in our case, a mix between a qualitative system diagram such as a CLD and a full computer simulation model) provides a platform for identifying and evaluating the relative merits of different policy and management actions. In line with Antunes et al., (2015), our results show that the SD model helped expand participant ideas about the range of potential policy and

management actions by showing system-wide points of intervention. It also facilitated the development and use of shared language and shared content among workshop participants.

4.1 Practical insights

The newly acquired understanding is relevant beyond the workshops and offers a range of practical insights for workshop participants. Here we elaborate on how the workshops provided participants with a differentiated evaluation of common practices such as piecework (laboring work), an appreciation of how the activities of men and women affect each other and how they are positioned within the entire food and farming system. Furthermore, we show how the workshops enabled participants to critically discuss how the government, particularly with its fertilizer subsidies, affects the working of reinforcing feedback loops between food production and income, and livestock and income, respectively.

Piecework

Short-term laboring work or piecework is an important coping strategy to ensure food security in the lean season (Kent & MacRae, 2010, Cole & Hoon, 2013). It is undertaken on other people's farm and labor is typically exchanged for cash or food. This exchange enables those short of food and/or cash to navigate through the lean season. However, it can have longer-term consequences in that it may restrict a farm's own ability to cultivate a sustained food supply (e.g., Whiteside, 2000). Discussing piecework as one option to fill up the water glasses on our diagrams lead to a differentiated evaluation of the short- as well as long-term impacts of piecework, not only on the cash variable, but also on all the other variables on the diagram:

- *ii_FP9 9: Yes, so I was saying the only common piecework we have here is weeding the fields for your friend, and they give you money; now I was saying this piecework here in the village, it is quite dangerous. You work in your friend's field, and do the weeding; in the mean time your field will lose out because of weeding for someone, and your crop will die in the grass.*
- *…*
- *ii_MP2: Piecework is not just cultivating your friend's field; yes piecework is in a lot of ways. Okay let's come back to the same issue of weeding for someone; for instance I get money, and I manage to do my field; and I finish all the programs. Now, there is no money in the house; now there comes, my bull is sick; then someone without oxen wants me to go and weed his maize with a cultivator, that's piecework. And now, I don't have the money, so in such a case; I need to go and weed his maize, in the meantime my field is already done, but then where to get some more money I don't have. So it's better for me to go and weed for someone, and after getting money; I can now go and buy medicine for the bull.*

One of the natural consequences of this differentiated evaluation of piecework as a coping strategy for farmers was to emphasize the need for proper planning. When reflecting on the

need for planning, participants transferred the insights from the discussion around piecework to other household decisions and activities:

- *i_MP5: Most importantly I have learnt that, one, I need to have a disciplined budget, because sometimes like some mentioned; the budget needs to be disciplined, for instance you have livestock, and you decide to sell one, treat this as a debt that you need to replace the animal. Because if you take it casually to say, this is my animal and it's okay if I sell it, it means you will not be able to replace it; it means your budget will be disturbed and so everything else will be disturbed. Then also, I have learnt that we need to set goals in everything we do; for instance school going children, usually it's not always that they make it to the next grade that we are required to pay school fees. But rather, it's once maybe the whole year, so if I didn't plan for this and it so happens that the only way out is to sell the food I reserved; imagine how much I would need to raise maybe the required say one thousand Kwacha or maybe if I had to sell some livestock, I would need maybe oxen to raise this money. Then, it simply means my livestock will be affected; and so the most important lesson I have learnt from this is the emphasis on our life circle, the way we need to live, and also the need we have to prepare for the future.*

Gender roles and their interconnections

The gender distribution among workshop participants was, by design, quite even. Although we never explicitly discussed gender issues, it was quite clear that men and women are responsible for managing different stock variables in our diagram. Gradually, workshop participants started reflecting on their own position within the diagram and the importance of their own or their spouses' decisions for the overall development of food security and livelihoods over time:

- *ii_MP3: Just there on the food reserves, you can do the preparation very well to such an extent that the reserves are full; yes you buy salt for the household, maybe it's actually a sack. Now when our spouses go to fetch water, they start boosting to their friends that we have a sack of salt; don't worry there is no problem. They give maybe a big cup full to their friend until finally the salt is finished, now the question is, will that bag last till the end of the year? It will not reach; which means a problem has now entered there (food availability).*
- *…*
- *ii_FP2: For instance the men, there (cash) I believe that they have understood, they will not be flirting around taking money to their mistresses; the money will be retained in the homes.*

Eventually, participants acknowledged that men and women in a household had to support each other if they wanted to reap the benefits of the reinforcing feedback loops:

- *i_MP2: Whatever we have discussed here if you try to break any of these; she can remind you, no no, this is not what we learnt.*
- *…*

- *i_MP2: So that as we go, we can be helping each other*

Role of the government

Another instance of transfer from issues that were explicitly portrayed on the diagram to related issues was a fairly extended discussion of how the government influenced the reinforcing feedback loop between cash and production:

- *i_MP2: We have seen how we are supposed to do things; … Yes government has introduced this fertilizer support program, but then this support program since inception, we find ourselves totally dependent upon it such that others have even died within this program. But then, when we look at this program, my question is; how helpful is this in helping us fill our cups or rather how does this prevent us from filling our cups?*
- *…*
- *i_MP3: Okay in short where we have shortcomings, the time we are given this fertilizer; normally they delay to give us the fertilizer.*
- *MF: So it comes very late.*
- *i_MP3: Yes Why I say so, it's because we learning conservation farming by ripping; now ripping requires that once you do the ripping, make sure you plant together with fertilizer. Now what happens is that this fertilizer is delayed, and so if you rip but you don't plant together with fertilizer, usually the maize doesn't do well; we have seen this from our friends and other people who don't use fertilizer when planting. Yes, the government does bring the fertilizer; but usually it comes very late, and if we very much rely on this, even if we desire to use the new methods of farming, this will not meet our desires, and hence our cups will not be filled because we shall be waiting for fertilizer.*
- *…*
- *i_MP2: So my question there is that, let's take it we are given on time, at one time we are given this; now next year, and the other year should I continue being with them so that I can continue filling my cup or should I plan there to come out, and be independent, and work on my own, and have my own source of income and work without expectation of these government policies?*

4.2 Workshop design features to support learning-by-doing

We had no experimental control that would have allowed us to explore how specific features and outcomes compare with other participatory learning and knowledge management strategies. We were mostly interested in better understanding if and how the adopted method would support farmers in learning about the interdependencies and dynamics of their food system.

Here, we reflect on some features that seemed beneficial for facilitating the observed mental model change. Our learning-by-doing approach can be closely linked to constructivist and experiential learning traditions, including conceptual change theories, which

acknowledge that situative, cultural and cognitive factors influence learning and mental model change. In this view knowledge develops actively through experience and approximation, is embodied and multi-modal, tool-dependent and shared (Greeno & van de Sande, 2007; Ernest, 1995; Kolb 2014). Diagrams, tangible objects and other artefacts play a central role and have shown to facilitate shared learning and help learners move from concrete, practice-based to more abstract understanding (cf. Ivarsson et al. 2002; Roschelle, 1992; Uttal et al., 1999).

In the workshops, a substantial amount of time (between 20 and 30%) was dedicated to the identification and discussion of concepts that then became variables in the jointly developed CLD. Using pictures and objects from familiar contexts seemed a crucial enabler in developing a more conceptual understanding of classifications in line with variable and stock definitions. This process of abstraction and classification is the very prerequisite for further development of any of the skills and concepts related to systems thinking. However crucial, the assumption about an a-priori conceptual understanding of variables seems so pervasive that it is not explicitly mentioned in existing systems thinking frameworks. We would argue, that it is worthwhile spending some time clarifying the definition of variables, also in other contexts.

Computer simulation is an important component of SD in general and of participatory SD in specific. Introducing computers and computer simulation models to our workshop audience, however, did not seem appropriate. Instead, we chose the analogy of the water glass to visualize stock variables in the CLD, to illustrate the behavior generated by the feedback loops in the diagram and to qualitatively simulate anticipated impacts of stressors and options.

Using water glasses provided a very powerful means to represent the effects of these stressors and options. Richardson (1986) discusses that even for experienced modelers, it is very hard to qualitatively assess the behavior of complex systems by only assessing the feedback loops presented in a CLD. For this reason, authors like Richardson (1986) and Homer and Oliva (2001) stress the importance of computer simulations to uncover counterintuitive responses of the system. In the proposed approach, this is the purpose of the water glasses. Pouring water into and from the glass, cannot account for non-linearities entirely or include all processes simultaneously and hence substitute the insights gained from computer simulations. It did however prove helpful in giving participants rules of thumb about how the system might react. The water glasses seemed to serve as a bridge for linking farmers' considerations about their real-world farming and food domain with the processes described in the CLD. This became clear initially during the reflection round in the workshops. The participants questioned the role of the government in supporting them to fill the glasses, voiced the need for teaching their spouses about the glasses and for planning with their spouses the decisions about glasses they needed to make at different times throughout the year. Then, the post-workshop interviews (one week as well as one year after) revealed that "filling the cups" had become a salient and powerful narrative for framing their issues and in the end guiding behavior and decision-making.

5 Conclusions

Resource users and managers such as small-scale farmers possess in-depth knowledge of their food system, together with associated management practices (Berkes et al., 2000). To be better prepared for and resilient to uncertainty and disturbances in the future, they need to further develop knowledge about the food and farming system as a system, with its dominating feedback structures and complexities. Such knowledge and understanding is critical for continuous adaptation and for testing robust and integrated system-based solutions (Holling, 2001, Wiek et al., 2011), as feedback structures and complexity often cause well-intentioned solutions to have unanticipated consequences (e.g., Moxnes, 2004; Sterman, 2008).

The purpose of this paper was to study participatory system dynamics in a context where qualitative causal loop diagramming (CLD) is not enough but at the same time, quantitative computer simulations are not suited for the purpose of building intuition about feedback structures and the dynamics they give rise to. We presented a simplified participatory system dynamics workshop design that substitutes computer simulations with a learning-by-doing approach and evaluates the outcomes of this workshop design in terms of mental model refinement. For this purpose, we ran two participatory SD workshops on food security and livelihoods with small-scale farmers in Zambia who struggle with recurrent food insecurity and the need to build adaptive capacity in the face of quickly changing and increasingly challenging framework conditions. We complemented the workshops with follow-up interviews to test the knowledge gained about the complex archetype structures underlying the system behavior.

Our analyses show that participatory SD is well adaptable to support an audience-specific learning-by-doing approach. The use of pictures, objects and water glasses in combination with the basic aspects of causal loop diagramming makes for a well-balanced toolbox. It provides incentives for engagement through familiar items from participants' day-to-day practice while at the same time posing conceptual challenges that need to be resolved in the group. Furthermore, the understanding of a relatively small number of system concepts is required to allow for a broad range of systemic considerations. These are: the concept of variables as independent entities, disentangled from their daily and procedural use; the conceptual understanding of causal relations between those entities; the conception of a closed loop; the concept of stock levels; the concepts of reinforcement and self-regulation; the concept of cross-impact; and the conception of dependence on initial states.

The two knowledge domains, concrete or practice-based knowledge and abstract knowledge, clearly interplay: one within which the participants hold knowledge of their real world farming and food domain and one that employs knowledge of the systems thinking domain. The further the process of causal loop diagramming, the less intense becomes the conceptual learning effort but the more complex and fluid becomes knowledge integration. In other words, while in the beginning participants are busy developing understanding of concepts from a systems perspective, in the end they are busy integrating them with other forms of knowledge in more complex tasks such as option development and evaluation.

While we focused on tailoring the participatory modeling exercise to groups at the community level with low or no formal educational background, the applications of this learning-by-doing approach are wider than that. There are other settings where computer simulations might not be appropriate or recommended, even when dealing with participants with a high level of formal education (cf., Coyle, 2000). If participants are not used to analyzing graphs or are unfamiliar with computer modeling techniques, charts produced during the simulation might be confusing, lead to wrong conclusions and diminish confidence in the process. In these contexts, and if the goal of the modeling process is learning rather than elicitation, participants might appreciate an interactive approach just as much or more than reading simulation output. Further research will have to study how and to what extent the approach tested in our case study farming communities in Zambia is scalable to other social-ecological systems and to other contexts of participatory system dynamics modeling.

Modeling of complex systems in a shared learning process such as the processes facilitated by participatory SD becomes more important than the model as a mere product for decision making (Dogliotti et al., 2014). However, it also becomes clear that systems thinking and knowledge integration are only one component of SES transformation. The specific systems thinking competences gained that allow participants to consider a broader variety of policy and management actions and to evaluate them in a different way, are still disconnected from any practical implementation. The current, implicit expectation of this knowledge strategy is that conceptual change and knowledge integration is a precursor to behavioral change. How to facilitate behavioral change from conceptual change, however, is a separate and challenging task. Further research thus needs to investigate which knowledge aspects or heuristics (e.g. “trying to fill the glasses”) have a potential to guide farmers in real-life monitoring, decision-making and finally implementation of policy and management actions to improve food system outcomes. Next steps in the participatory SD process also need to include more explicitly power and interest issues and their heterogeneity among and across a variety of stakeholders at a variety of levels (e.g., Enfors et al., 2008, Cote & Nightingale, 2011). Such research will help systems thinking and participatory SD move beyond one-time-learning to providing tools for continuous, informed and reflective systems action.

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7 Supplementary information

Supplementary information 1: Episode during workshop phase 1 where participants develop a basic understanding of variables. MF – male facilitator. FP – female participant. MP – male participant. PS – participant that could not be identified in the video or audio file. The episode is taken from the second of the two case study workshops (hence the denotation ii_).

TURN	PARTICIPANT	TALK	ACTION SPECIFICS	DEVELOPING SHARED UNDERSTANDING
153	MF	Okay then, have we seen this one?	Holds up picture of fertilizer and seed packs	
154	ii_PS	Yes.		
155	MF	Where is it going; is it going on fertilizer? What is this?		
156	ii_FP1	It's fertilizer.		
157	MF	Yes, where does this go?		
158		Give her!	Hands picture to participants	
159	ii_FP8	This one?	Points at other female	
160	MF	No!	Hands picture to FP8	
161	ii_FP8		Places picture of fertilizer and seed with label *land*	After the picture is identified to show fertilizer, FP8 places the picture of fertilizer and seed packs with the label *land*, which indicates that for her, these two form a meaningful combination. Under what circumstance does it make sense to put fertilizer and seeds on land? From the daily viewpoint of a small-scale farmer it makes every possible sense. Seeds and fertilizer are supposed to go on the land; it is their ultimate use and destiny. Her action indicates knowledge of how one farms and what procedures need to be followed when farming. Her view resonates intensely with at least one more participant (FP2). She is not alone in approaching the task from this specific viewpoint. However, in the context of the task situation this is not the only possible way of framing, and for that matter, not the appropriate one. Some of the other participants utter disagreement, they seem to have taken a different perspective.
162	MF	This one here looks doubtful!	Points at FP1	
163		And you, also doubted?	Indicates FP2	
164	ii_FP2	No; I didn't doubt!		
165		That's the right place.		
166	MF	That's the right place?		
167	ii_PS	No!		
168	ii_FP3	*Mumbling* – let me see!	Points at picture	
169	ii_FP2	No,	Points at *land*	
170		it is supposed to go to soil.		
171	ii_MP3	Can I put – is it allowed?	Attempts to take the picture, but removes hand	MP3 takes the picture and places it with the label *food produced*. Now, what can be his motivation and understanding to put it there? Most likely, MP3 has taken a more conceptual, less process-oriented view. From his standpoint, seed and fertilizer are necessities for the larger context of food production. Hence, he places them as smaller units within the larger conceptual unit of food production. Just as with FP8, this conception is not wrong. It makes perfect sense in itself and could fit the required principle. However, the underlying guiding principle calls for categorical attribution of what things "are" according to the labels present, as opposed to localized process attribution ("where and how they are used") or sectorial attribution ("what they are used for").
172	MF	Yes can you place it!		
173	ii_MP3		Removes picture of fertilizer and seed, looks at it and at the labels and places it with the label *produced food*	
174	MF	Now, where will this picture be placed?		
175	ii_FP3	No! No, no...		Also, MP3's suggestion is met with disagreement from large parts of the group. After his attempt has failed to offer an option viable for agreement in the group,
176	ii_FP	Na, naaa...		
177	ii_FP2	Keep it on the soil!	Points at *land*	
178	MF	Yes		
179	ii_MP1		Removes picture of fertilizer and seed packs	
180	ii_FP8	This we do plant!	Points at *land*	
181	ii_FP1, ii_FP4		Points at *inputs*	FP1, FP3 and FP4 start pointing at *inputs*. MP1 takes initiative and removes the picture one more time and places it in *inputs*. MP2 underlines his colleague's move by asserting: "These are

182	ii_F P3	Oha!	Points at *inputs*	inputs", which is repeated by MP1 in agreement and gives insight into their now appropriate understanding. They employ their conceptual knowledge on categorization accordingly and satisfy the requirements and possibilities set by both, the underlying concepts and the material at hand. FP1 and FP4 further develop and elaborate on his point, however not extensively. The facilitator also acknowledges the placement of the picture and explicitly tries to secure common ground.
183	ii_M P1		Puts picture of fertilizer and seed with label *inputs*	
184	ii_M P2	These are in-puts.		
185	ii_M P1	These are in-puts, ya ya.		
186	ii_F P1	Yes, just there;	Points at *inputs*	
187		on the ploughs, fertilizer and seed!	Points at *inputs*	
188	ii_F P4	All is going there.	Points at *inputs*	
189	MF	Yes, we have seen that, isn't it!	Gestures at *inputs*	
190	ii_P S	Yes.		
191	MF	We haven't yet started identifying where these things work!	Specific gesture (points of influence) referring to diagram in general	Furthermore, the facilitator now offers a framing by distinguishing the current task from a possible future task that takes into account an understanding more similar to that of FP2 and FP8 (where things "work" and "go", a paraphrase for cause-effect relationships). The group jointly arrives at this insight after having gone through a process of stating, challenging, testing and finally aligning their understanding under conditions of categorization.
192		No, we are just putting them in?	Specific gesture (groups) referring to diagram in general	
193	ii_F P(8)	In order!		
194	MF	In order!		
195		Yes, after putting those in order, that's when, we'll now say this one works where; here! This one goes where; here.	Tracing gesture	
196	ii_F P	Oh, okay!		

Notes regarding the development of shared understanding

Turn 161-170: After the picture is identified to show fertilizer, FP8 places the picture of fertilizer and seed packs with the label land, which indicates that for her, these two form a meaningful combination. Under what circumstance does it make sense to put fertilizer and seeds on land? From the daily viewpoint of a small-scale farmer it makes every possible sense. Seeds and fertilizer are supposed to go on the land; it is their ultimate use and destiny. Her action indicates knowledge of how one farms and what procedures need to be followed when farming. Her view resonates intensely with at least one more participant (FP2). She is not alone in approaching the task from this specific viewpoint. However, in the context of the task situation this is not the only possible way of framing, and for that matter, not the appropriate one. Some of the other participants utter disagreement, they seem to have taken a different perspective.

Turn 171-173: MP3 takes the picture and places it with the label food produced. Now, what can be his motivation and understanding to put it there? Most likely, MP3 has taken a more conceptual, less process-oriented view. From his standpoint, seed and fertilizer are necessities for the larger context of food production. Hence, he places them as smaller units within the larger conceptual unit of food production. Just as with FP8, this conception is not wrong. It makes perfect sense in itself and could fit the required principle. However, the underlying guiding principle calls for categorical attribution of what things "are" according to the labels present, as opposed to localized process attribution ("where and how they are used") or sectorial attribution ("what they are used for").

Turn 175-180: Also, MP3's suggestion is met with disagreement from large parts of the group.

Turn 181-190: FP1, FP3 and FP4 start pointing at inputs. MP1 takes initiative and removes the picture one more time and places it in inputs. MP2 underlines his colleague's move by asserting: "These are inputs", which is repeated by MP1 in agreement and gives insight into their now appropriate understanding. They employ their conceptual knowledge on categorization accordingly and satisfy the requirements and possibilities set by both, the underlying concepts and the material at hand. FP1 and FP4 further develop and elaborate on

his point, however not extensively. The facilitator also acknowledges the placement of the picture and explicitly tries to secure common ground.
Turn 191-196: Furthermore, the facilitator now offers a framing by distinguishing the current task from a possible future task that takes into account an understanding more similar to that of FP2 and FP8 (where things "work" and "go", a paraphrase for causeeffect relationships). The group jointly arrives at this insight after having gone through a process of stating, challenging, testing and finally aligning their understanding under conditions of categorization.

Supplementary information 2: Episode during workshop phase 3 where participants develop an understanding of the behavior that reinforcing feedback loops give rise to. MF – male facilitator. FF – female facilitator. FP – female participant. MP – male participant. PS – participant that could not be identified in the video or audio file. The episode is taken from the second of the two case study workshops (hence the denotation ii_).

TURN	PARTICIPANT	TALK	ACTION SPECIFICS	DEVELOPING SHARED UNDERSTANDING
514	MF	What if… or better still we start with the cash!	Pointing at *cash* Pours water out of cup by *cash*, puts cup back to *cash*	At this stage, the participants share understanding of some basic conceptions, such as causal links, mutual influence or impact. There are, however, differing approaches and degrees of detail in reasoning, indicating a fair amount of mismatch in understanding and perspectives taken. Furthermore, the construction of understanding based on the conception of a closed loop seems very fragile and cannot be fully realized. Instead, the participants continue to rely on the conception of individual links and their anticipated dynamic connection. Hence, reasoning is based on participant's conceptual understanding of the components and their particular interrelationships. FP1's explanation does not satisfy the requirements necessary to reason in terms of a closed loop concept, nor does she employ reasoning about specific links. She develops an explanation that incorporates broad knowledge on some relationships while embedding her story in a personal, yet hypothetical situational context (522–525). She activates her conceptual understanding of the interplay of some general system components and combines it with conceptions of self, expectation, failure and success.
515		What if only this remains; then?		
516	ii_MP1	Then it means things are disturbed!		
517	MF	Ähä! Then...		
518		*incomprehensible cross-talk, FP1 talks to MF*		
519	MF	Ahää!		
520		Now; let us do this,		
521		can you explain what will happen step by step! Can you explain this first! There, if you disturbed the cash there; then what is going to happen?	Specific gesture (step-by-step) referring to diagram in general Pointing at *cash*	
522	ii_FP1	If there is any mistake there on the cash; I believe if I had any expectations to say this year this is what I will do after production, and then unfortunately the cash is halved,	Pointing at *cash* Pointing at *cash*	
523		the expectations you had fail;		
524		So it will mean all the programs will be halved.	Gesturing to unspecific parts of the diagram	
525		They can't succeed if there on the cash, it is half.	Pointing at *cash*	
526	MF	Aha.		
527		Okay, anyone with a contribution; yes!		
528		Who has a contribution on the fact that,	Pointing at *cash*	
529		if there is a disturbance on the cash there!	Specific gesture (disturbance) referring to *cash*	
530		Then now; what will happen there on the implements?	Pointing at *inputs*	
531	ii_MP1	If the money reduces,		After FP1, mainly MP1 together with the facilitator create a narrative, which is closer tied to the diagram and the individual aspects of the system. Starting from *cash*, each connection and its dynamic implication are explored. Similar to FP1, he activates conceptual knowledge on those interconnections, but does so in a sequential and specific way determined by the diagram. Over the course of two argumentative turns, MP1 increasingly gains conceptual agency.
532		it means now the inputs are disturbed.		
533		You will only get very little according to the money you have.		
534	MF	Oh! Very little, small!	Gesturing towards *inputs*	
535	ii_MP	Ähh!		
536	MF	Okay!		
537	ii_MP1	Yes, because of the reduction in monetary terms and so the in-puts will be very little.		
538	MF	Ahä!		
539	ii_MP1	Then now we come there on food production;	Pointing at *produced food*	
540		so it means the food that will be produced there will be very little.		
541	MF	Okay!		
542	ii_MP1	Yes, because now the harvest will do what?	Pointing at *produced food*	For another two turns MP1 steps in the role of the challenger himself. Together

543	MF	Reduce!		with the facilitator (taking on the role of a group participant), FP2 and FP3 they explore two more links and their dynamic relation until reaching *available food*. Interestingly, even before MP1 goes on to question about the effect on *available food*, FP3 takes the next step and anticipates the answer through gesturing downwards. Subsequently, it is also expressed verbally, and then the facilitator takes over.
544	ii_MP1	Yes, it will reduce;		
545	ii_FP3		Specific gesture (reducing) directed at *available food*	
546	ii_MP1	So now going there to food availability,	Pointing at *available food*	
547		so it means also the food will be what?	Pointing at *available food*	
548	ii_FP2 + ii_FP1	Not sufficient!	Specific gesture (not sufficient) relating to *available food*	
549	MF	It has reduced!		
550	ii_MP1	Yes, also there it has reduced.		
551	MF	Yes; now when the food reduces,	Gesturing over *available food*	He further challenges MP1 to explore the relation with *cash* through food surplus. This leads MP1 to close the loop in the narrative and to keep developing it further. Consequentially, he creates a new insight on loop polarity and the downward trend. A new understanding is constructed organizing available information in line with the principles of a feedback loop.
552		then the surplus for sell now?	Tracing gesture from *available food* to *cash*	
553	ii_MP1	It means there is nothing or maybe just very little.		
554		Since the money will reduce,		
555	ii_FP1	*mumbling*	Tracing gesture from *cash* over *inputs* and *land* to *produced food* Gesturing over *available food* Tracing gesture from *available food* to *cash*	
556	ii_MP1	it means now it's a serious problem!		
557		Everything goes down.		
558	MF	He's saying that in the long run you die because things are reducing...	MF translating to FF Tracing gesture around the loop Specific gesture (reduction over time) sequentially along the loop	
559		So maybe, we do this?		
560	FF	Okay... good afternoon!		
561	MF	Yes! Maybe, we do this;		
562		We have seen at first to say, if this increases here, it increases there, and then everything will be okay.	Pointing at *available food* Specific gesture (increasing) referring to *available food* Specific gesture (increasing) referring to *cash* Tracing gesture around the loop	Finally, the facilitator helps the group repeat and stabilize this understanding by jointly going around the loop again and again until full alignment of their perspectival understanding is realized.
563	ii_PS	Mhmm		
564	MF	Then the second lesson, we saw to say; if you disturb the cash there,	Specific gesture (disturbance) referring to *cash*	
565		which means there?	Tracing gesture from *cash* to *inputs*	
566	ii_MP1	The things are disturbed.		
567	MF		Specific gesture (reduction) referring to *inputs*	
568		And also here?	Tracing gesture from *inputs* to *produced food*	
569	ii_PS	They are also disturbed!		
570	MF		Specific gesture (reduction) referring to *produced food* Tracing gesture from *produced* to *available food*	
571	MF	Then now which means the following year?	Pointing at *cash*	
572	ii_MP1	There will be very little that you will have there.		
573	MF	So, even next year?		
574	ii_MP1	It will reduce further.		
575	ii_MP2		Specific gesture (reduction) referring to diagram in general	
576	MF	Oh, they will be further reduced?!	Specific gesture (reduction) referring to diagram in general	
577	ii_PS	Yes.		
578	MF	They will go down; oh!		
579	ii_PS	Yes.		
580	MF	Okay!		

Notes regarding the development of shared understanding:

Turn 514-525: At this stage, the participants share understanding of some basic conceptions, such as causal links, mutual influence or impact. There are, however, differing approaches and degrees of detail in reasoning, indicating a fair amount of mismatch in understanding and perspectives taken. Furthermore, the construction of understanding based on the conception of a closed loop seems very fragile and cannot be fully realized. Instead, the participants

continue to rely on the conception of individual links and their anticipated dynamic connection. Hence, reasoning is based on participant's conceptual understanding of the components and their particular interrelationships. FP1's explanation does not satisfy the requirements necessary to reason in terms of a closed loop concept, nor does she employ reasoning about specific links. She develops an explanation that incorporates broad knowledge on some relationships while embedding her story in a personal, yet hypothetical situational context (522- 525). She activates her conceptual understanding of the interplay of some general system components and combines it with conceptions of self, expectation, failure and success.

Turn 531-540: After FP1, mainly MP1 together with the facilitator create a narrative, which is closer tied to the diagram and the individual aspects of the system. Starting from cash, each connection and its dynamic implication are explored. Similar to FP1, he activates conceptual knowledge on those interconnections, but does so in a sequential and specific way determined by the diagram. Over the course of two argumentative turns, MP1 increasingly gains conceptual agency.

Turn 542-550: For another two turns MP1 steps in the role of the challenger himself. Together with the facilitator (taking on the role of a group participant), FP2 and FP3 they explore two more links and their dynamic relation until reaching available food. Interestingly, even before MP1 goes on to question about the effect on available food, FP3 takes the next step and anticipates the answer through gesturing downwards. Subsequently, it is also expressed verbally, and then the facilitator takes over.

Turn 551-557: He further challenges MP1 to explore the relation with cash through food surplus. This leads MP1 to close the loop in the narrative and to keep developing it further. Consequentially, he creates a new insight on loop polarity and the downward trend. A new understanding is constructed organizing available information in line with the principles of a feedback loop.

Turn 562-580: Finally, the facilitator helps the group repeat and stabilize this understanding by jointly going around the loop again and again until full alignment of their perspectival understanding is realized.