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Contribution of systems thinking and complex adaptive system attributes to sustainable food production: Example from a climate-smart village

Renata Jagustović[a,*], Robert B. Zougmoré[b], Aad Kessler[a], Coen J. Ritsema[a], Saskia Keesstra[a], Martin Reynolds[c]

[a] Department of Environmental Science, Wageningen University and Research, PO Box 47, 6700 AA Wageningen, the Netherlands
[b] CGIAR Research Program on Climate Change, Agriculture and Food Security (CCAFS), International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), BP 320, Bamako, Mali
[c] School of Engineering and Innovation, Faculty of Science, Technology, Engineering and Maths, The Open University, UK

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ABSTRACT

Climate-smart agriculture (CSA) conceptually has the potential to contribute to the sustainable development goals of achieving zero hunger, reducing land degradation, eliminating poverty, tackling climate change, and promoting gender equality. The scaling-up needed to achieve goals of CSA represents a challenge, as it entails understanding synergies between often opposing socioeconomic and environmental priorities and trade-offs over temporal and spatial scales. In this paper, we tested new approaches to support scaling-up of sustainable food production through investigating the contribution of systems thinking as a conceptual approach and complex adaptive system (CAS) attributes as a framework for analysis of CSA. This was done through examining (i) to what extent CSA represents a CAS and (ii) what contribution systems thinking and CAS attributes can make to understanding and scaling-up sustainable food production systems through CSA. The CSA situation was conceptualized through systems thinking sessions with women farmers in the climate-smart village (CSV) of Doggoh-Jirapa, northern Ghana, and was guided by the Distinctions, Systems, Relationships and Perspectives (DSRP) framework. Systems thinking, and CAS attributes provide system-wide understanding of elements, dynamics and trade-offs over temporal and spatial scale in selected agri-food systems. As such it could aid horizontal and vertical scaling-up by informing policy developoment and selection of a context-specific portfolio of technologies and practices at landscape and farm levels to achieve synergies between goals. In this study, systems thinking enabled women farmers in the CSV to identify income-generating and tree planting activities, with desirable simultaneous system-wide impact. The paper calls for further testing of tools, approaches, and methods that enable dynamic systems thinking to inform scaling-up efforts, while embracing the transdisciplinary nature and complexity of CSA as a constituent of the food production system.

1. Introduction

In view of today's 795 million hungry and the additional 2 billion people expected by 2050, there is an urgent need for a change of global food and agriculture systems in order to sustainably increase food production (UN, 2016). Recognizing that food production systems are complex and multisectoral, especially in the context of climate change and variability in sub-Saharan Africa, scaling-up of climate-smart agriculture (CSA) is seen as a relevant solution for tackling sustainable increases in food production. CSA integrates the social, economic and environmental dimension of food production and aims to simultaneously achieve the triple goals of (i) ensuring food security through a sustainable increase in productivity and income, (ii) adapting to climate change and (iii) reducing greenhouse gas emissions (FAO, 2013; Campbell et al., 2014; Zougmoré et al., 2014). Scaling-up CSA calls for an integrated landscape-level approach that includes climate-smart practices at farm, village and landscape levels (Scherr et al., 2012) as a pathway to sustainable food systems. CSA does not necessarily call for new agricultural technologies, but for harmonization and synchronization of agricultural interventions to achieve synergies and manage short and long-term trade-offs between the triple goals (FAO, 2013). As a mix of effective CSA interventions depends on the context of the food production system, the type of interventions will differ from one context to another.

* Corresponding author at: Department of Environmental Science, Wageningen University and Research, PO Box 47, 6700 AA Wageningen, the Netherlands.
E-mail address: renata.jagustovic@wur.nl (R. Jagustović).

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While CSA has the potential to bring us closer to safe operating spaces for agricultural and food systems to meet food security needs (Neufeldt et al., 2013), barriers to scaling-up remain (Neufeldt et al., 2015; Aggarwal et al., 2018; Loboguerrero et al., 2017; Westermann et al., 2015). Recent studies examine approaches and barriers to horizontal (i.e. replicating proven practices, technologies or models in new geographic areas or targets) and vertical (i.e. institutional and policy change demonstrating efficiency and effectiveness of practices, technologies, and models) scaling-up of CSA. Aggarwal et al. (2018) investigated the climate-smart village (CSV) approach to aid horizontal and vertical scaling-up. The CSV approach is applied with local communities and their partners to test, through participatory methods, technological and institutional options for dealing with climate change risks to agriculture. It generates evidence at local scales of which climate-smart agricultural options work best, where, why, and how, and use this evidence to draw out lessons for policy makers, agricultural development practitioners, and investors from local to global levels. However, the study also acknowledged the need for greater evidence for the CSV approach in different agro-ecological environments, understanding the trade-offs in current and future socioeconomic and climate scenarios and evidence that adaptation strategies do not become maladaptive. Westermann et al. (2015) identified multi-stakeholder platforms, policy making networks, capacity building, and learning as significant to support decision-making of farmers and to scale-up CSA. Furthermore, Loboguerrero et al. (2017) found that climate services and insurances are a potential tool to scale CSA by providing an enabling environment for the adoption of CSA practices while protecting against the impacts of climate extremes. Neufeldt et al. (2015), in a bid to support scaling-up of successful CSA practices, examined eight case studies in South Asia and put forward a tool comprising of seven elements that practitioners and policy makers can use to address challenges and opportunities for scaling-up. They conclude that scaling-up CSA is a long-term, non-linear process that requires combining generalized and context-specific approaches, as well as both horizontal and vertical scaling-up.

There is a recognition that establishing sustainable food systems through scaling-up CSA depends on the understanding of the interdependencies of context-specific socioeconomic and environmental elements (Steenwerth et al., 2014; Aggarwal et al., 2018), and their dynamics at different temporal and spatial scales. It is in this perspective that investigations in agri-food systems were conducted applying systems thinking and complex adaptive system (CAS) attributes. Hammond and Dubé (2012) developed a system approach framework, and proposed the use of transdisciplinary modelling tools, such as system dynamics modelling (SDM) and agent-based modelling, to capture dynamic and adaptive processes within and between interconnected systems. These authors argue that food security and nutrition challenges could be better assessed using a systems approach. Furthermore, Monasterolo et al. (2016) claim that multidimensionality and complexity of assuring food security is not possible through sector-specific or agricultural productivity models, as they cannot represent their nonlinear and time-dependent relations. The authors concluded that despite the complexity of the agri-food system, there is prevalence for traditional modelling and a smaller but growing number of complex system models. They argue for systematic analyses of the contribution of both approaches in order to inform evidence-based policies for sustainable and inclusive agriculture. Banson et al. (2014) investigated the contribution of systems thinking to understand behaviour of agribusiness system in Ghana and identify leverage points for systemic interventions.

However, systems thinking as a conceptual approach and CAS attributes as a framework for analysis have not yet been employed to investigate their contribution to scaling-up of CSA. Considering the need for synergies and understanding trade-offs over temporal and spatial scale, any approach to inform scaling-up should aid identification of context-specific interventions to achieve the desirable triple goals of CSA. This study therefore investigated (i) the extent to which CSA in the CSV of Doggoh-Jirapa represents attributes of a complex adaptive system (CAS), and (ii) the potential of systems thinking as a conceptual approach and CAS attributes to inform vertical and horizontal scaling-up, considering a non-linear dynamic portfolio of climate-smart practices and technologies, emerging reality, and socioeconomic and environmental context.

2. Complex adaptive systems and systems thinking: conceptual background

2.1. Complex adaptive systems (CAS): a theoretical framework for analysing CSA

Development problems, including food security, are increasingly seen as systems comprising tightly coupled physical, social and ecological sub-systems which, due to interdependences, resist unilateral solutions and call for a new approach to conceptualizing and finding solutions (Richmond, 1993; Head and Alford, 2015). A system renders a set of connected interdependent elements as a web of interrelationships, producing a pattern of behaviour seen by someone as generating a purpose (Meadows, 2009; Morris, 2009 p.16; Reynolds, 2016). CAS are systems whose behaviours emerge as a result of nonlinear interrelations, on different spatial and temporal scales, among a large number of elements without central control (Chan, 2001; Mitchell, 2009; Eidelson, 1997). The idea of CAS was originally formulated as a way of making sense of natural phenomena (cf. Holland, 1992, 2006). The body of knowledge pertaining to CAS is extensive, hence this section does not aim to provide a review of the complexity theories, but rather to introduce and define five CAS attributes as a theoretical framework for analysing CSA. These attributes are (i) Many Interconnected Elements and Open System, (ii) Feedback Loops and Time Delays, (iii) Dynamic Nature, (iv) Self-Organizing and Emergent Order, and (v) Robustness and Resilience.

2.1.1. Many interconnected elements and open system

CAS comprises many diverse, interconnected elements within a system and between a system and its environment (Chan, 2001; Begun et al., 2003; Abraham et al., 1997). CAS are open systems, meaning that elements and systems outside of the observed system boundaries and its control have an impact on the system and vice versa. Identifying boundaries of the system - "what is in" - can be difficult, and boundaries are normally determined by the purpose of the description of the system and influenced by the position of the observer (Cilliers, 1998).

2.1.2. Feedback loops and time delays

CAS are nonlinear in nature and are dominated by feedback loops. Feedback loops are a closed sequence of cause and effect relationships between elements: when a change in one element leads, after some time, to a change in the same element (Pruyt, 2013). Feedback loops (Fig. 1) can be reinforcing ("+") or balancing ("−").

A feedback loop is called reinforcing, indicated by sign "+", if an initial change in a variable "A" leads after some time to an additional change in the same direction in "A", or if it contains an even number of negative (−) causal links. In isolation, reinforcing feedback loops are self-enhancing and generate exponentially escalating behaviour which could be (extremely) beneficial or (extremely) detrimental (Pruyt, 2013). When reinforcing feedback loops dominate the system, they can - depending on the system state - lead to tipping points and system transformation.

A feedback loop is called balancing, indicated by sign "−" if a change in variable "A" leads after some time to a change in the opposite direction in "A" or if it contains an odd number of negative (−) causal links (Pruyt, 2013; Kanti et al., 2017). A balancing feedback loop can generate balancing or goal-seeking behaviour and is a source of stability as well as resistance to change. However, the presence of a balancing

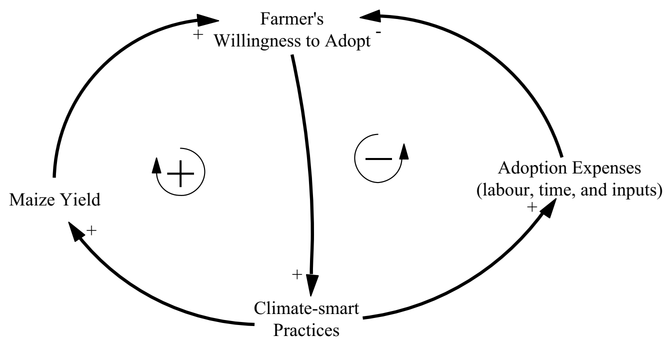


Fig. 1. Example of Reinforcing (+) and Balancing (−) feedback loops in the context of CSA.

(−) feedback loop in a system does not imply that the objective will be achieved nor that the process is under control, as it can also cause undesirable behaviour (Sterman, 2001).

In feedback loops with delay there is a time delay between taking a decision and its effects. Furthermore, the long-run response of a system to an intervention is often different from its short-run effects (Sterman, 2001). Different short and long-term responses enable the system to cope and adapt to change in order to sustain its function (Cilliers, 1998). The longer the delays in feedback loops and the more indirect the consequences, the more difficult it is to recognize the feedback structure (Pruyt, 2013) and its impact. Feedback loops do not exist in isolation and two or more feedback loops are connected into a feedback system. The dominance of feedback loops shifts over time (i.e. one feedback loop loses strength while another gains), and complex system behaviour arises due to the shifts in strength of different feedback loops within the system (Pryut, 2013).

2.1.3. Dynamic nature

The dynamic nature of a system assumes that its elements are constantly revising their rules for interaction. Each element is facing novel surroundings due to the changing behaviour of the other elements that provide stimuli. The aggregate behaviour of the system continues to evolve due to simultaneous interactions among elements (Holland, 1992; Chan, 2001). The interconnectedness of the elements within a system ensures that any stimuli from inside and/or outside the system triggers changes within the system, between the system and the outside environment, and back to the system (Sterman, 2001). Due to the dynamic nature and constant action and reaction to what “others” are doing, nothing is static, and CAS constantly change and evolve, presenting a “moving target” (Holland, 1992).

2.1.4. Self-organizing and emergent order

CAS are self-organizing: the system behaviour arises without an internal or external controller or leader due to the interaction between the components of a system (Mitchell, 2009; Cilliers, 1998; Chan, 2001; Eidelson, 1997). Through simple IF (input/condition) - THEN (output) rules between elements (Holland, 1992, 2006; Cilliers, 1998), CAS produce complex system behaviour that is hard-to-predict. Elements interact simultaneously by sending and receiving signals, and each element adapts its behaviour to accommodate the behaviours of elements with which it interacts. The interaction between elements (IF-THEN) defines influence and interrelationship. The higher the degree of interrelations between elements, the more complex the system, and the more difficult it is to understand.

Changes in any relationship will affect all system elements. The emergent system behaviour comes about through lower level interaction of less complex elements and rules (Mitchell, 2009; Levin, 2010; Abraham et al., 1997) and cannot be understood by looking at the behaviour of its elements alone (Holland, 1992). CAS emergent state often arises due to a shift in feedback loop dominance.

2.1.5. Robustness and resilience

Robustness is the capability of a CAS to continue functioning in the face of disturbance (Marion and Bacon, 1999). Robustness at the system level emerges from the absence of robustness at the individual element level (Levin, 2010). As complex systems change and adapt in response to conditions within or outside the system, they possess a range of coupling patterns between elements, from tight to loose (Marion and Bacon, 1999). Loosely coupled structures cushion and moderate responses to strong shocks, while more tightly coupled structures tend to “lock-in” and present a challenge for system adaptation (Marion and Bacon, 1999).

Resilience is the capacity of a system to absorb disturbance and reorganize to retain essentially the same function, structure, identity, and feedback system (Walker et al., 2004). System robustness emerges, to a large extent, from interactions at much lower scales between individual agents, short-time scales, and small spatial scales – and feedback to influence the dynamics of the whole system. When systems are in the undesirable emergent state, we want to overcome their robustness; or in the case of the desirable emergent state, we want to maintain them (Levin, 2010).

2.2. Systems thinking: an approach to conceptualizing and scaling-up CSA

Whilst complexity science and systems thinking could aid dealing with development problems including food security issues, some have argued that a lack of an agreed systems thinking definition may hinder the development and application of systems thinking skills (Arnold and Wade, 2015; Monat and Gannon, 2015). Indeed, one significant challenge of the research reported here was how to render the climate-smart village (CSV) of Doggoh-Jirapa in northern Ghana as a complex adaptive system – particularly as seen from the perspective of the women farmers - to inform scaling-up of CSA.

Systems thinking can be understood as a shift from conventional thinking that (i) facilitates understanding the complexity of the whole rather than focusing on its component parts (Reynolds and Holwell, 2010; Behl and Ferreira, 2014), and (ii) considers interdependent relationships and views a problem as a dynamic, interdependent, and ongoing process (Richmond, 1993). The Open University system academics consider Systems Thinking in Practice (STiP) as primarily an epistemological (learning) endeavour. The STiP heuristic comprises three core activities: (i) understanding inter-relationships (uIR), (ii) engaging with multiple perspectives (eMP), and (iii) reflecting on boundary judgements (rBJ) (Reynolds and Holwell, 2010; Reynolds, 2016). Systems thinking to ensure food security through climate smart agriculture (CSA), investigated in this paper, is thus primarily an endeavour to make sense of and improve the complex realities of (unsustainable) food production, from the perspective of women farmers in the village of Doggoh-Jirapa.

Drawing on the STiP heuristic, systems are (conceptually) bounded entities subject to boundary reflection. Reflecting on boundaries requires attention to our limitations and partiality regarding: (i) being holistic - some selection is required since not *all* inter-related entities can be bounded; and/or (ii) being pluralistic – viewpoints are always biased hence any boundary judgements must inevitably be partial towards some perspective (Reynolds, 2011, 2016). The three constituents of the STiP heuristic (understanding inter-relationships, engaging with multiple perspectives, and reflecting on boundary judgements) address four traps of mainstream thinking about systems in practice in general (Reynolds, 2008), and specifically in agriculture - including aspects of CSA:

- Reductionism (not including relevant inter-related elements)
- Dogmatism (assuming a singular ‘expert’-driven perspective regarding ‘the’ system)
- Holism (assuming certainty that *all* inter-related elements are included)

- Pluralism (assuming impartiality and that *all* relevant stakeholders are involved)

In operationalizing STiP for the fieldwork with stakeholders in Ghana we used a cognitive framework of systems thinking designed by Cabrera and Colosi (2008) drawing on four simple rules - Distinctions, Systems, Relationships, and Perspectives (DSRP). Reynolds (2008) and Reynolds and Holwell (2010), Cabrera (2006), Cabrera and Colosi (2008) and Cabrera et al. (2008) all regard systems thinking fundamentally as a cognitive epistemological endeavour. Cabrera and colleagues acknowledge that while systems thinking is informed by systems ideas, methods, theories, and sciences, in the end, it is a mental capacity based on the pattern of thinking.

3. Methodology

3.1. Context of fieldwork and general framework for the systemic inquiry

Doggoh-Jirapa CSV is the agricultural "research for development" site led by the Savannah Agricultural Research Institute of the Council for Scientific and Industrial Research (CSIR_SARI) and supported by the CGIAR Research Programme on Climate Change Agriculture and Food Security (CCAFS). Since 2011 the CCAFS research programme, in collaboration with the CSIR-SARI and the Doggoh Jirapa community, has been testing climate-smart technologies and practices. The CCAFS baseline data at household, village and organizational level (available at: http://hdl.handle.net/10568/24838) collected through the CCAFS research programme in 2011 and 2012, informed site selection and methodology (Onyango et al., 2012). Baseline data showed that food production was characterized by rain-fed production of maize, groundnuts, cowpeas, rice, beans, sorghum, and yams. It also showed that the village population produced enough maize for only three months of the year, having to purchase maize for the remaining nine months through the sale of other crops. In addition, the sale of wood for fuel was putting pressure on the tree population with evidence of degradation and lack of community mechanisms for regulating wood harvesting for sale, cooking and charcoal production. The same baseline data noted a difference in the management of trees that fall on communal land (open access) and those that fall on individually owned land (controlled access).

In the Doggoh-Jirapa CSV, systems thinking was operationalized through the DSRP framework (described in 3.2), which informed selection of data collection methods and tools to facilitate systems thinking with women farmers. In the following sections, we refer to the "conceptualized CSA system" as the outcome of four systems thinking sessions undertaken during the fieldwork with the understanding that the described system is always relative to the perspective from which the understanding or frame was made (i.e. the women farmers). As the research was introduced as part of CCAFS efforts to generate evidence in collaboration with local communities, this could have also potentially framed the perceptions of the women as to the expectations of the researcher. The research design attempted to address this challenge by (i) building relationship of trust by spending time in the CSV and involving a local language translator familiar to the women, (ii) operationalizing the DSRP framework to develop the methodological approach – process, data collection tools and key questions for each session, (iii) facilitating systems thinking sessions acknowledging that outcomes are framed by the women farmers' "view" of CSA, and (iv) refraining from suggesting elements, relationships and dynamics not identified by the women.

3.2. The DSRP framework

The DSRP framework (Table 1) is seen as an essence of systems thinking, comprised of four cognitive patterns (rules) that are universal to various systems thinking subfields and methods (Cabrera et al., 2015) and can facilitate understanding complex systems (Cabrera et al., 2008).

Table 1
DSRP pattern of thinking (Cabrera et al., 2008; Cabrera et al., 2015).

Rule	Element 1	Element 2
Distinction (D)	Thing/idea/concept	Other
System (S)	Part	Whole
Relationship (R)	Action/Cause	Reaction/Effect
Perspective (P)	Point/Subject	View/Object

The DSRP framework proposes four conceptual patterns (rules) for systems thinking – Distinction (D), System (S), Relationships (R), and Perspective (P), each comprised of two elements (Table 1). The four rules can be aligned with the three attributes of STiP: (i) understanding inter-relationships (Relationship), (ii) engaging with multiple perspectives (Perspective) and (iii) reflecting on boundary judgements (System and Distinction). The DSRP should be understood not as a set of four rules but a theoretical framework of interactions of the four rules and its elements (Cabrera and Colosi, 2008).

The Distinction (D) rule implies that we make a distinction between and among things, concepts, and ideas, implying the existence of an 'other': a wider context or situation from which conceptual distinctions are made. Making distinction involves setting boundaries that determine what is part of the system and what is not (Cabrera et al., 2008).

The System (S) rule assumes identifying parts and wholes of an object of our interest and organizing parts and wholes into alternative nested systems. The system rule assumes that one cannot consider a part without considering the whole (cf. Shaked and Schechter, 2013; Behl and Ferreira, 2014), and thing, concept, or idea is simultaneously a part and a whole. The rule implies that recognizing systems involves breaking things down into their constituent parts and grouping parts into larger wholes.

The Relationship (R) rule calls for recognizing the bi-directional properties (affect and effect) of each element, and that relationships can take innumerable forms, such as feedback loops, correlations, and causalities. The Relationship rule enables examining systems as the parts of a whole that can be connected in multiple ways, and it is the relationships between and among things that lead to complexity.

The Perspective (P) rule assumes that any concept carries with it a frame of reference, and a perspective taking allows for viewing one concept (e.g. CSA) from a generic viewpoint as well as a more specific point of view (Cabrera et al., 2008). A perspective can be seen as a lens through which we view the world, and its objects, which allows us to see the object of our investigation from the perspective of the other.

Finally, the DSRP rules are interdependent, forming a complex system of interaction (Cabrera and Colosi, 2008); they occur simultaneously throughout the systems thinking process, and one rule cannot be applied without the presence of the other rules.

3.3. Data collection: systems thinking with women farmers

The systems thinking sessions with women farmers were conducted by the researcher with support of a local language translator. As part of preparation for data collection, introductory meetings with a local language translator were held to review the session plan, and discuss terminology, research objectives and the strategy for engagement with the community. Meetings with the village chief, local government, and local partner CSIR_SARI were held to gain access. An introductory meeting with the village community was held to introduce the researcher and translator, clarify the purpose of the study, and gain consent. During the meeting fifteen women farmers were randomly selected to choose a sample which would be representative of the female population in the village. A lottery technique was used, where each woman was assigned a number, and all numbers were mixed and selected randomly for participating in the systems thinking session. Prior to commencing with the systems thinking session, the researcher observed the portfolio of climate-smart interventions and demonstration sites, interacted with community members and Extension Officers, and observed on-going livelihoods activities.

The DSRP framework informed the process and the selection of tools to facilitate each systems thinking session and gain a holistic understanding of CSA from the women farmers' perspective. The tools used to facilitate systems thinking sessions included brainstorming, bulls-eye diagram, graphs over time, group discussions, nominal group technique, an aggregated preliminary (seed) model, and a Causal Loop Diagram (CLD) (Andersen and Richardson, 1997; Hovmand et al., 2013; Chambers, 1992; Kim, 1994; Ager et al., 2015). With regard to the goals, the tools used to facilitate systems thinking could be divided into (i) divergent tools to produce an array of different ideas and interpretations, (ii) convergent activities designed for clustering and categorizing (aggregating) ideas and interpretations, (iii) tools to evaluate ideas/data in order to choose and/or rank, (iv) tools to aid participants' verification of data collected (Andersen and Richardson, 1997), and (v) CLDs to visualize the CSA situation. The CLD supported visualizing elements of the system, interconnectedness between elements, and identifying the principal feedback loops of the systems responsible for generating dynamic behaviour (Kanti et al., 2017). The outcome of each session was verified by the local language translator and the women farmers and served as an input for the next session.

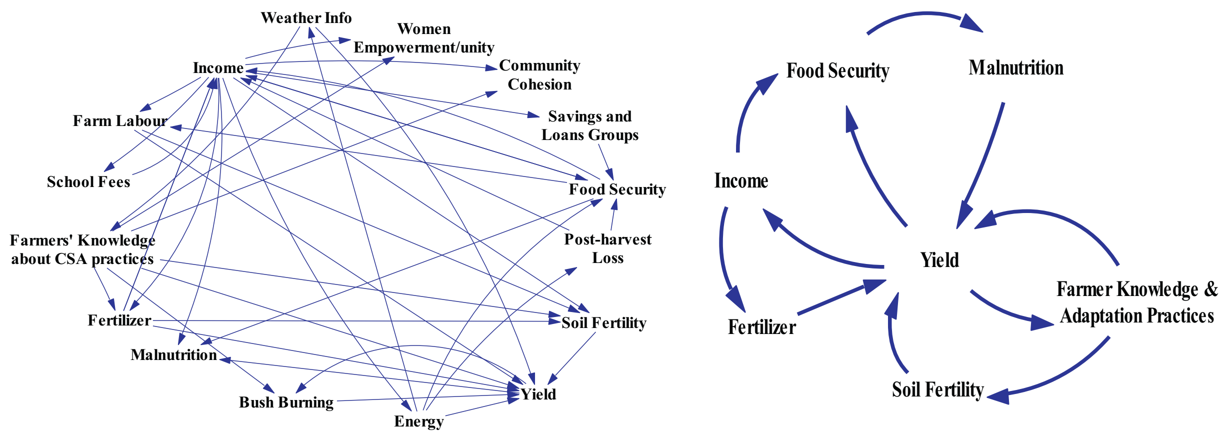
Table 2 summarizes the methodological approach to operationalize systems thinking in Doggoh-Jirapa by illustrating (i) dominant DSRP basic rule guiding session design (i.e. process, tools, questions), (ii) dominant DSRP dynamic observed during each session by the researcher, (iii) dominant STiP elements dynamic, (iv) systems thinking tools used by the resercher during each session, and (v) dominant CAS attributes observed as an outcome of each session. The arrows indicate that the output (dashed line) from each session was used as an input for the next, as well as the non-linear nature (full line) of the systems thinking process.

Data collected was recorded using flipchart papers, visual index cards, and photographs. Raw data was transcribed daily as textual files. Vensim Professional 6.4a (Ventana Systems, Inc.) software for system dynamics modelling was used to transfer outcomes of the sessions to a digital format and visualize CSA in the form of a CLD. To construct the CLD, a "variable tool" was used to enter all elements, and an "arrow tool" connected elements to replicate the dynamic story illustrated in the CLD constructed during the sessions. Once the basic cause-effect structure was established connecting elements, arrow links were labeled to illustrate IF-THEN relationships as "+" or "−" using the links "polarity tool." Using the "common tool", the feedback loops were labeled as reinforcing "+" or balancing "−" (result shown in Figs. 3 and 5). Vensim's "causes and use tree" function was used to produce a visual illustrating direct and indirect cause and effect relationships between elements (Fig. 4). The "loops tool" was used to determine the elements of the feedback loops and the length of the feedback loops for any selected element.

Session 1: This session clarified the purpose of the data collection through systems thinking and initiated discussion about CSA and what the main elements of CSA are in the context of Doggoh-Jirapa village and the women farmers' perspectives. Guided by the Distinction (D) rule, women farmers were invited to reflect on their understanding of what "is" and "is not" CSA. Participants discussed in pairs and shared their responses with the larger group. A group discussion was held to seek common agreement as to what does and does not constitute CSA. Once agreement was reached, the nominal technique was used to identify the main elements that constitute CSA from the women's perspective. Discussion was used to clarify the meaning of the elements,

Table 2
Methodological approach used to operationalize systems thinking and complex adaptive system (CAS) – Distinction, System, Relationship, Perspective (DSRP) framework, Systems Thinking in Practice (STiP) heuristic and core activities (i) understanding inter-relationships (uIR), (ii) engaging with multiple perspectives (eMP), and (iii) reflecting on boundary judgements (rBJ), systems thinking tools, and dominant complex adaptive system (CAS) attributes (Authors).

Systems Thinking Sessions	DSRP: DSRP Basic rule	DSRP: Dominant DSRP Dynamic	Dominant STiP Dynamic	Tools for Systems Thinking	Dominant CAS Attributes
Session 1	Distinction (D) Concept-Other	PDSR	uIR/rBJ/eMP	Nominal Group Technique, Group Discussion, Bulls-eye Diagram.	Many Diverse Elements & Open System
Session 2	Relationship (R) Action - Reaction	PRDS	eMP//rBJ uIR	Influence Graph; Graph over Time; Seed Model	Many Interconnected Elements & Open System
Session 3	System (S) Part-Whole	PRSD	eMP/uIR/rBJ	Causal Loop Diagram (establish influence, and IF-THEN relationships)	Self-Organizing & Emergent Order
Session 4	System (S) Part-Whole	PSRD	rBJ/eMP/uIR	Causal Loop Diagram (identifying feedback loops, feedback systems thinking, identifying interventions system-wide impact, assuming impact through feedback systems thinking)	Feedback Loops & Time Delays; Dynamic Nature; Robustness and Resilience; Many Diverse Elements & Open System



(a) Drivers and outcomes (b) CSA preliminary influence model

Fig. 2. Perspectives of Women Farmers.

and as needed redefine them, introduce new elements and/or aggregate elements. The bulls-eye diagram was used to facilitate identifying the main CSA elements within the village boundaries and omit elements outside the village boundaries.

Session 2: Following the verification of Session 1 outcomes, the group was asked to determine the direct influence of each element identified in Session 1 on the other elements. Cards depicting elements identified in Session 1 were placed on a large paper and the researcher drew arrows illustrating direct influence (Fig. 2a) as stated by women. A counting method was used to identify the dominant drivers (arrows going out) and outcomes (arrows going in) constituting the preliminary influence (seed) model (Ager et al., 2015) (Fig. 2b).

In an attempt to look into the dynamic over time for key elements, the use of graphs over time was demonstrated and the women were asked to analyse the dynamics of key elements over the last five years and to note changes. As the women preferred to narrate how each dynamic changed rather than to illustrate the change on the graph, the translator or researcher recorded the dynamics reported by the women.

Session 3: This session commenced with the validation and elaboration of the preliminary (seed) model from Session 2 and a review of the dynamics over time for the key elements. The preliminary (seed) model was displayed, and the women farmers were each given cards with visual representations of elements of the CSA identified in Session 1. Starting from the displayed model, the group reflected on "What does X impact?" and "What impacts X?" This prompted the women to identify relationships between the seed model and other elements.

Cards were placed and arrows drawn indicating relationships between elements. The cause and effect relationships between elements were reviewed, omitted relationships identified, and more arrows drawn. After establishing cause-effect relationships between different elements, the second part of the session determined IF-THEN dynamics. Starting from "yield", women farmers were asked to determine IF "yield" increases, do other elements impacted by yield THEN increase or decrease? When the women indicated that a change in one variable caused a change in the same direction in another variable, the sign "+" was placed next to the arrowhead. If a change in one variable caused a change in the opposite direction, the sign "−" was placed next to the arrowhead. This process continued until all IF-THEN relationships were established. During this stage, the group also noted additional cause and effect relationships and IF-THEN dynamics. Post-session, the researcher transferred the CLD developed during the sessions into digital form using Vensim software (Fig. 3) and visually re-organized the structure to facilitate the women farmers' review and validation.

Session 4: The objective of the session was to review and validate the CLD and identify prominent feedback loops and interventions that the women perceived would bring system-wide positive changes in Doggoh-Jirapa. First, the systems thinking process was summarized, and women farmers were invited to identify other missing elements, cause-effect relationships between elements, and interrelations. Thereafter, the concept of feedback loop was defined as "when a change in one element after some time leads to a change in the same element". The researcher pointed to an example of a feedback loop on the CLD, and then invited the women to review the CLD and identify and describe other feedback loops recognizing the IF-THEN dynamic. To facilitate the identification of dominant feedback loops, women were asked "what are the most important dynamics they observe in the village today?" Lastly, women were asked to discuss and identify interventions that could bring positive changes and scale-up CSA. The group was taken through feedback systems thinking (Reynolds and Holwell, 2010) using the constructed CLD and insights gained during the previous session, including a graph over time (i.e., reduction in number of trees, increase in women's workload), to establish possible impact. The selected feedback loops and interventions were marked on the CLD and post-session transferred into digital form using Vensim software (Fig. 5). Following the identification of key interventions the women reflected on the systems thinking process and CLD representing CSA.

4. Results

4.1. CSA system in Doggoh-Jirapa from women farmers' perspective

As an outcome of the systems thinking sessions, the CLD (Fig. 3) illustrates the present-day CSA system state in Doggoh-Jirapa village from the women farmers' perspective. With regard to the concept of CSA (Session 1), women focused on practices and technologies introduced through the CCAFS project with a focus on climate adaptation and yield increase. Mitigation, as one of the goals of CSA, was not identified. The CSA system as perceived by women farmers comprises seventeen elements inside the boundaries of the Doggoh-Jirapa CSA system (in black), two elements outside the system boundaries (in green), and interventions (in red) for scaling-up CSA. The CLD shows direct cause and effect relationships (arrows), IF (condition/action) - THEN (reaction) relationships ("+" and "−" signs on arrows), and feedback loops as identified by women farmers.

The elements with a large number of cause-effect relationships (arrows going in and out) are food security, maize yield, climate-smart practices, women's workload, financial assets, and trees on communal land.

Women farmers in Doggoh-Jirapa distinguished between "climate-smart practices" that require labour (e.g. growing on ridges,

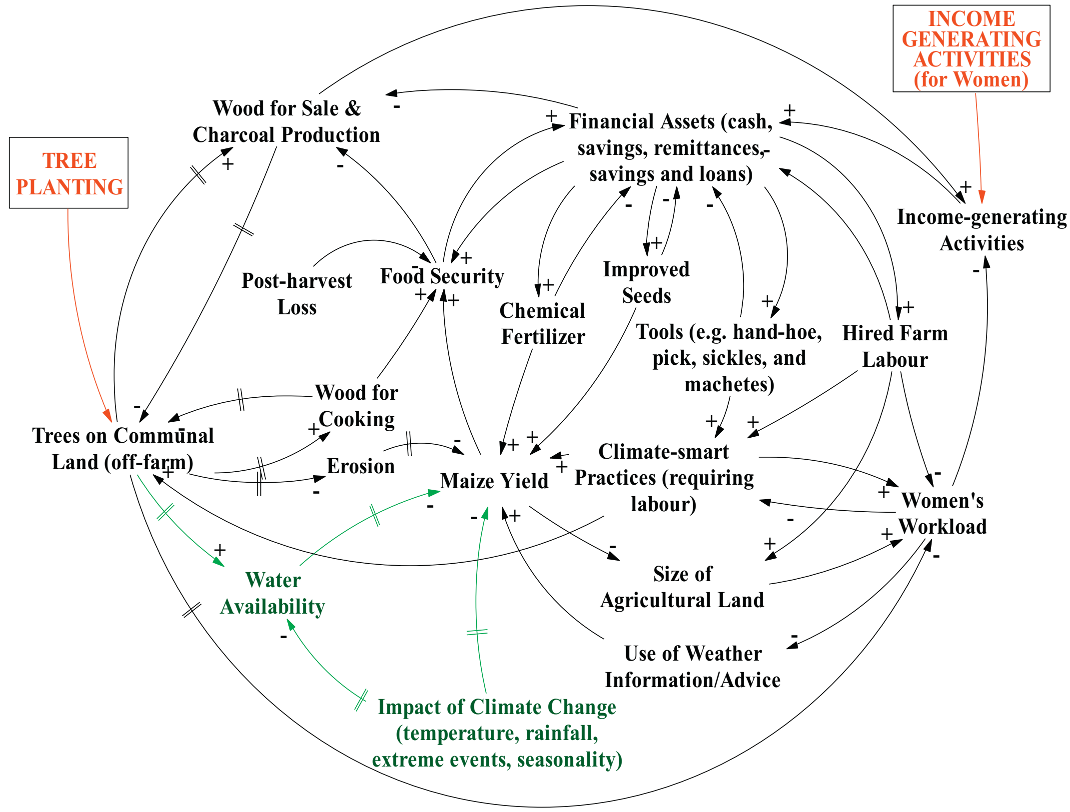


Fig. 3. CLD representing the Doggoh-Jirapa CSA system from the perspective of women farmers.

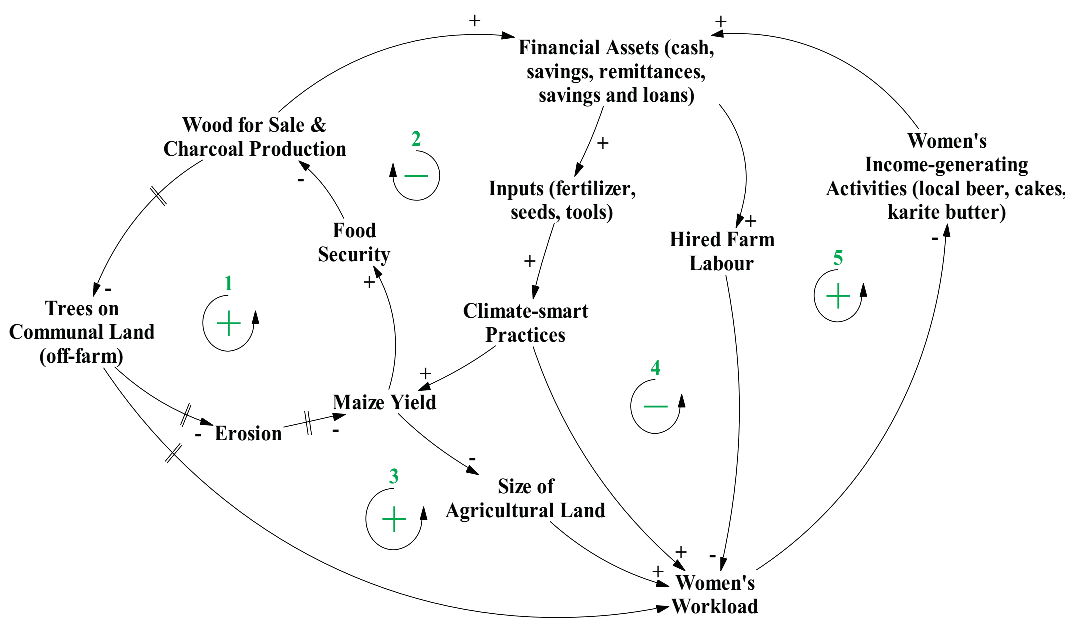


Fig. 4. Dominant feedback loops responsible for emergent system state in the Doggoh-Jirapa CSV.

intercropping, weeding, spacing, growing in rows, composting, etc.), and those that require financial assets (e.g. tools, chemical fertilizer, seeds, weather information, etc.). They also recognized that an increase in "climate-smart practices", "use of weather information", "seeds", and "chemical fertilizer" will lead to an increase in "maize yield". The women stated that they do not act on weather information due to workload, as working on their plots is possible only when work on the men's farms is completed and tools are available. This means that they often miss the optimal time (according to weather information) for various farming practices.

By reflecting on the dynamics over time, (Session 2) the women noted that (i) (increased) soil erosion leads to decrease in maize yield, (ii) that (increased) charcoal production and wood for cooking leads to a decrease in tree cover and increased erosion, and (iii) (increase) in the use of chemical fertilizer due to new varieties of maize seeds leads to both increased need for financial resources and increases in maize yield.

They identified “water availability” and “impact of climate change” as the most significant elements outside the boundaries of the system with an impact on the CSA. They also identified the link between the number of “trees on communal land” and “water availability”: if the number of “trees on communal land” decreases, then “water availability” will also decrease.

Reflecting on the systems thinking process and CLD in Session 4, the women noted:

- ✓ *“we cannot believe we came up will all this”* (referring to the CLD and all connection),
- ✓ *“often when we are doing something men will ask why we are doing it, it is not important; but now we see how it is important and how it impacts different things”,*
- ✓ *“tools are owned by men and we cannot use them until men are done with work; now we see how tools are connected to adaptation practices and yield increase; maybe we should buy our own tools so we do not depend on the tools the men use”,*
- ✓ *“everything is connected, so whatever we do will have an impact on something”,*
- ✓ *“we need to understand what we can do that has a positive impact on our lives”.*

4.2. Dominant feedback loops in Doggoh Jirapa

In Session 4 the women farmers identified five dominant feedback loops (Fig. 4.) and identified activities that would bring system-wide positive changes.

The following dominant feedback loops were identified;

- The reinforcing (+) feedback loop (1) with time delays (i.e. two lines on the arrows), shows that continuous exploitation of “trees on communal land” to achieve food security leads to increased “erosion” and, over time, an impact on “maize yield.” Left without intervention, the feedback loop in isolation could lead to exponential growth of erosion and further yield decrease.
- The balancing (−) feedback loop (2) on the other hand illustrates how “wood for sale and charcoal production” leads to an increase in “financial assets” that allow for the purchase of inputs and implementation of “climate-smart practices.” This leads to an increase in “maize yield” and “food security” that then marginally reduces exploitation of “wood for sale and charcoal production.”
- In addition, feedback loops 3, 4, and 5 illustrate direct and indirect causes of an increase in “women's workload” and how it impacts “maize yield” and “financial assets.”
- The reinforcing (+) feedback loop (5) illustrates that an increase in “women's workload” leads to a decrease in “financial assets” that can be used to “hire labour”, and results in further increase in “women's workload” as women do most of the work on the farms. Simultaneously, a reduction in “financial assets” leads to a reduction in a number of “climate-smart practices”, as inputs needed cannot be purchased. This in turn leads to a reduction in “women's workload” as observed in balancing (−) feedback loop 4.
- Finally, a longer reinforcing (+) feedback loop (3) illustrates that a reduction of “climate-smart practices” leads to a reduction in yield and food security, which consequently leads to an increase in the “sale of wood and charcoal production”, a reduction of “trees on communal land” and a further increase in “women's workload”.

To achieve system-wide positive impact, women farmers identified two interventions (i) intensifying tree planting to meet needs for wood for sale and cooking, and erosion control, and (ii) intensifying and diversifying income-generating activities for women to access the financial resources needed to purchase inputs and hire farm labour to reduce women's workload and increase maize yield (Fig. 3).

5. Discussion

5.1. CSA through CAS Lenses

In this section, CSA conceptualized through the systems thinking sessions with women farmers in Doggoh-Jirapa is analysed applying CAS attributes to establish to what extent it represents a CAS.

5.1.1. Many interconnected elements and open system

According to the perception of the women farmers, CSA in Doggoh-Jirapa comprises many interconnected socio-economic (e.g., income, hired labour, financial assets, women's workload) and environmental elements (e.g., rainfall, erosion, trees on communal land), indicating the transdisciplinary nature of the CAS. The arrows representing cause and effect relationships indicate a high level of connections and interrelationships, as the elements are connected either directly or indirectly. As an illustration, in Fig. 4, the women farmers identified seven direct causes (thick arrows going in) and two direct effects (thick arrows going out) between maize yield and other elements within the conceptualized system. This interconnectedness allows identification of indirect cause and effect relationships and dynamics between elements in different domains and on different spatial scales (e.g., impact of the number of trees at landscape level on maize yield at farm level).

The elements outside the system (e.g., climate change, water availability) with impact on CSA at the village level point to an open system and fuzzy boundaries. This together with the many interconnected elements found in Doggoh-Jirapa indicates that this attribute of CAS is present.

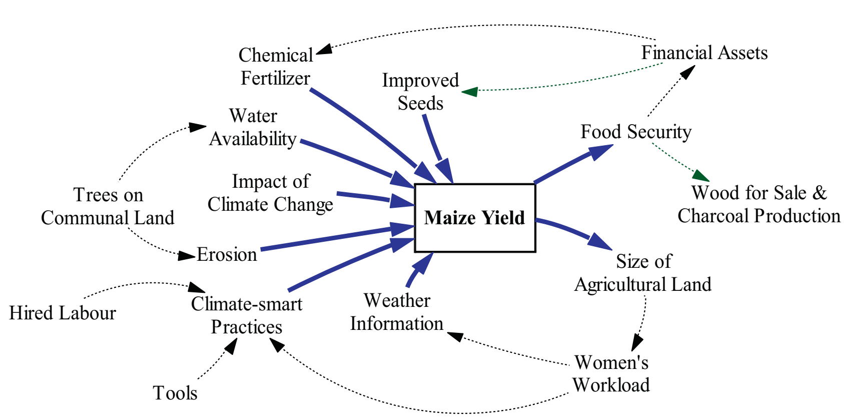


Fig. 5. Socio-economic and environmental elements with direct (thick arrows) and indirect (dotted arrows) cause (left side) and effect (right side) on maize yield.

5.1.2. Feedback loops and time delays

Analysing the CLD (Fig. 3) using Vensim software, numerous reinforcing and balancing feedback loops could be identified (e.g., "maize yield" is included in 84 feedback loops, "financial assets" in 101, "food security" in 83, "women's workload" in 84, "trees on communal land" in 74, and "climate-smart practices" in 80.) This indicates the nonlinear nature of CAS, and the dominance of feedback loops in the Doggoh-Jirapa CSA system. The observed feedback loops comprise various socioeconomic and environmental elements and are connected into feedback systems contributing to the dynamic nature and complexity of CSA.

Some of the reinforcing feedback loops also have time delays. For example, loops 1 and 2 in Fig. 4 illustrate that reduction of trees on communal land leads over time to a decrease in maize yield and an increase in women's workload. Due to time delay between action and reaction, the impact cannot be observed immediately and leads to environmental and social trade-offs. The five prominent feedback loops (Fig. 4) illustrate the system level dynamics aimed at (i) securing financial assets needed to apply climate-smart practices and hire labour, (ii) securing sufficient maize yield, (iii) increasing dependence on, and exploitation of natural resources, and (iv) increasing women's workload.

5.1.3. Dynamic nature

The CLDs (Figs. 3 and 4) allow visualization and verification of the dynamic nature of CSA, as they illustrate numerous direct and indirect connections between elements within and outside the system and feedback loops. As elements send signals (e.g., decrease in maize yield or increase in climate-smart adaptation practices), the other elements within and outside the system will react based on the signals sent. For example, a decrease in the number of trees will have a direct impact on women's workload as women walk longer distances to collect trees, and an indirect impact on financial assets, hired labour, climate-smart adaptation practices and maize yield. The decrease in the number of trees will also trigger changes between the system and elements outside the system over time, having an impact on rainfall and maize yield through an increase in soil and wind erosion. This further illustrates the dynamic nature of CSA, as each element in various domains sends and receives signals and simultaneously impacts and is impacted by other elements, and indicates the presence of another attribute of CAS.

5.1.4. Self-organizing and emergent order

The self-organizing attribute of CAS is also present in CSA as evidenced through IF-THEN (i.e. input-output) rules between elements represented by "+" or "−" on the arrows. These simple IF-THEN rules between elements are responsible for various reinforcing (+) and balancing (−) feedback loops within the CSA system. The prominent feedback loops (Fig. 4) are responsible for emergent CSA system state. The present emergent state is centred on increases in maize yield, women's workload, and securing financial assets. The emergent state can explain how some interventions focusing on specific elements without considering the system-wide impact can lead to unpredicted trade-offs and can cause unexpected aggregate behavior in the short and/or long-term. For example, potential unforeseen trade-offs are increases in women's workload due to climate-smart adaptation practices, and increased need for financial assets (in order to purchase inputs for CSA) that leads to soil erosion and a decrease in yield. This is because a need for financial resources is met through the sale of wood and charcoal, hence decreasing the tree density and adversely affecting erosion and eventually yield.

5.1.5. Robustness and resilience of CSA

Both robustness and resilience can be observed in Doggoh-Jirapa CSA system as elements - due to their direct or indirect connectivity and "flexibility" - adapt their responses based on the stimuli. For example, when maize yield is low, the sale of wood for charcoal will increase to gain income and meet food security needs, thus demonstrating the resilience of the elements within the system to absorb and reorganize. At the same time, when yield is high, the sale of wood and charcoal will decrease. Each element within the CSA system demonstrates a certain level of flexibility or resilience to absorb the shock to the whole system. Based on the dominant feedback loops, the present-day robustness of the system comes from reliance on natural resources (trees for sale and charcoal production) and an increase in women's workload to absorb shocks and meet the needs for income and food security. Considering that all attributes of CAS can be found in the Doggoh-Jirapa CSA system, it can clearly be considered to be a CAS.

5.2. Contribution of systems thinking and CAS attributes to scaling-up CSA

In Doggoh-Jirapa the DSRP framework provided a way of enacting systems thinking in practice (STiP) and conceptualization of CSA from the women farmers' perspective as opposed to conceptualization using conventional mainstream perspectives of CSA. Conceptualizing the agri-food system through a women farmers' perspective contributes to informing horizontal scaling-up by identifying context-specific opportunities and challenges to the adoption of CSA practices. Furthermore, it supports our understanding of how the present conceptualisation of the system emerged and what modifications could be introduced to transform the system to more sustainable food production through CSA.

This study also addresses the three challenges of scaling-up CSA though a CSV approach identified by Aggarwal et al. (2018) (i) evidence for CSV approach, (ii) understanding the trade-offs in current and future socioeconomic scenarios, and (iii) evidence that adaptation strategies do not become maladaptive. As evident in our example, analysing an established CSV site using systems thinking and CAS attributes (i) gives system-wide understanding as to what worked, and (ii) exposes unforeseen trade-offs leading to maladaptation at different temporal and spatial scale and diffrent domains. Hence, our approach shows potenital to inform both horizontal and vertical scaling-up, especially in the context of a CSV approach.

The system-wide understanding of impacts and trade-offs, considering context-specific dynamics, which is possible with feedback systems thinking, provides a solid basis for horizontal upscaling CSA adaptation strategies, practices, and technologies to new sites.

From women's closing remarks, it is evident that systems thinking increased the women farmers' understanding of CSA as a system. Based on the interventions that the women farmers identified as having system-wide positive impact, it is evident that this approach has great potential to facilitate (i) the adoption of CSA practices, (ii) taking actions that can have long-term sustainable impact (such as planting trees), and (iii) the women farmers' empowerment and equity.

However, the potential traps of systems practice noted in Section 2.2 may also relate to this study. The CAS established through the women farmers' participation may not have involved all relevant elements (i.e., there was no reference to mitigation of greenhouse gas emissions, hence it was inevitably reductionist). Furthermore, the conceptualized CSA system is explicitly from the perspective of women in Doggoh-Jirapa and thus may not reflect perspectives of other groups in other places. This is potentially problematic for transferring/translating options for scaling-up to other areas. It is important that the specific findings of this project not be looked at dogmatically, and rather that the systems thinking employed be seen as a means to identify effective scaling-up strategies for other areas.

6. Conclusion

The study findings suggest that CSA, as organized in the Doggoh-Jirapa CSV, is a highly complex adaptive system (CAS). CAS attributes, as a theoretical lens, facilitated the understanding of complexity, the dynamic-adaptive nature of the CSA system, and how to achieve synergies between the triple goals of CSA on the temporal and spatial scale. Results from the application of sensitivity and emergent attributes show that a lack of understanding of the system-wide dynamics responsible for the emergent system state leads to undesirable change in the short-term (i.e., increase in women's workload) or long-term (i.e., decline in trees on communal land leading to erosion and yield decrease).

Systems thinking applying the DSRP framework allowed "seeing" of the whole CSA situation from the women farmers' perspectives, and helped them identify transdisciplinary elements of CSA, their interrelations, sub-systems, and prominent feedback loops. Through this process, our understanding of the women farmers' perceptions of the CSA system, its elements, sub-systems, dynamics, and boundaries was enhanced, as was the women farmers' knowledge about CSA and their own situation.

Systems thinking and the CAS theoretical framework supported an understanding of trade-offs over temporal and spatial scales between the immediate short-term gain (e.g., income) and the long-term negative impact (e.g., reduction of trees and maize yield). The feedback systems thinking guided women farmers in understanding the dynamics behind an emergent system state and the identification of key interventions for achieving long-term desirable system-wide impact.

As such, we conclude that the use of systems thinking and CAS attributes is an effective and valuable approach to informing and effecting horizontal scaling-up by aiding the identification of the context-specific mix of CSA technologies and practices to achieve synergies between the triple goals of CSA. Understanding dynamics and emergent system state in existing CSVs through use of the tools and approach demonstrated in Doggoh-Jirapa could support generating evidence as to what worked and why to inform both vertical and horizontal scaling-up.

The investigation in Doggoh-Jirapa applying systems thinking and CAS attributes confirms (Steenwerth et al., 2014; Aggarwal et al., 2018) claims that establishing sustainable food systems through scaling-up CSA depends on the understanding of the interdependencies of context-specific socioeconomic and environmental elements and their dynamics at different temporal and spatial scales. However, the high level of complexity in CSA systems poses challenges to fully understand the adaptive and dynamic aspects through systems thinking as a conceptual approach. Building on this paper, both the contribution of system dynamics modelling as a tool for dynamic systems thinking to guide scaling-up CSA models, and the contribution of systems thinking as a conceptual approach to mobilize communities for adoption of sustainable CSA practices, will be investigated further.

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