Modelling agricultural innovations as a social-ecological phenomenon

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Abstract

Agricultural innovations involve both social and social-ecological dynamics where outcomes emerge from interactions of innovation actors embedded within their ecological environments. Neglecting the interconnected nature of social-ecological innovations can lead to a flawed understanding and assessment of innovations. In this paper, we present an empirically informed, stylized agent-based model of agricultural innovation systems in Mali, West Africa. The study aimed to understand the emergence of food security and income inequality outcomes through two distinct model structures: top-down, aid-driven (exogenous) innovation and bottom-up, community-driven (endogenous) innovation. Our research questions were: i) How does the inclusion of social-ecological interactions in the model affect food security and income inequality outcomes? ii) How do exogenous and endogenous mechanisms influence food insecurity and income inequality? iii) What are the conditions under which exogenous and endogenous mechanisms would improve food security? The structural design of the model was based on a combination of theory, empirics, and mapping of social-ecological dynamics within innovation systems. Using the Social-Ecological Action Situation framework, we mapped the social, social-ecological, and ecological interactions that jointly produce food security outcomes. The exploratory model analysis reveals three key insights: i) Incorporation of social-ecological interactions influences model outcomes. Scenarios with social-ecological interactions showed a stronger relationship between income inequality and food security, lower levels of food security, and higher levels of income inequality than scenarios with social interactions. ii) Endogenous mechanism leads to higher food security and income inequality than the exogenous mechanism. iii) Bidirectional outreach is more effective than unidirectional outreach in improving food security. Inclusion of social-ecological dynamics and interactions such as the role of climate risk perception, social learning and formation of innovation beliefs and desires is key for modelling and analysis of agricultural innovations.

Keywords

Stylized models, Social-Ecological Systems, Agriculture, Innovations, Agent-based models

Code availability

The model code for the agricultural innovation (Ag-Innovation) agent-based model can be found in COMSES https://www.comses.net/codebases/80397098-9368-40ab-bb01-56b5f929ea04/releases/1.0.0/

1. Introduction

Agricultural innovations play a crucial role in agricultural development, productivity improvement, environmental sustainability, and poverty reduction (Röling, 2009) and are integral for addressing global hunger, malnutrition, and food insecurity. Innovations are vital for resilience, adaptability, and flexibility (Moore et. al.,

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Cite this article as:
Sanga, U., Berrío-Martínez, J., & Schlüter, M.
Modelling agricultural innovations as a social-ecological phenomenon
Socio-Environmental Systems Modelling, vol. 5, 18562, 2023, doi:10.18174/sesmo.18562

Socio-Environmental Systems Modelling
An Open-Access Scholarly Journal
http://www.sesmo.org

2012) and can foster adaptive responses to changing social-ecological conditions (Olsson & Galaz, 2012). The understanding of agricultural innovations has evolved over the last several decades. According to Klerkx et al. (2012), who studied the evolution of thinking in agricultural innovation, in the 1950s to 1970s, innovation was viewed as a linear process of scientific invention of technologies that were then transferred to and adopted by the intended users (see also Godin & Lane, 2013). In several countries, agricultural innovations were funded by external aid, developed in controlled research environments by scientists, and disseminated through extension services for adoption by individual farmers (Valente & Rogers, 1995; Faure et al., 2018). The 1980s saw a shift in focus from external aid-driven technology transfer to community participation, learning, and ownership (Klerkx et al., 2012). Both scientists and farmers were viewed as central actors who undertook innovation development, dissemination, and diffusion roles through shared knowledge and resources (Hall & Clark, 2010; Brooks & Loevinsohn, 2011). Innovation systems came to be seen as a collection of entities or agents (individuals, organizations, institutions) that form '*a complex web of layered and nested connections that cross the typical space, time and sector boundaries…*' (Moore, 2017 pg. 219). This presents a dynamic, systems perspective of the process of innovation which arises from the actions and interactions of agents embedded within a social context operating at different scales, and hence, termed 'social' innovation (Nicholls & Murdock, 2012).

However, agricultural innovations are not purely social processes but also include ecological dimensions. Olsson & Galaz (2012) highlight the complex, intertwined nature of social-ecological innovations. In the context of agricultural sustainability, examples of such social-ecological dimensions include the influence of climate and ecological factors in innovation development and adoption, biophysical feedback from the implementation of agricultural technologies such as changes in crop yield, soil fertility, etc. Conceptualizing innovation solely as social processes and ignoring social-ecological interactions may result in maladaptive outcomes and misleading or myopic appraisals of the impact of innovation. Examples of such maladaptive outcomes include the Green Revolution in Asia in the 1960s that resulted in environmental damage and soil degradation despite significant increases in crop yields (Pingali & Rosegrant, 1994), or the development of agricultural innovations for increasing maize productivity suitable for certain agro-ecological zones in Kenya but without adequate consideration of social or ecological realities of the drier zones (Leach et al., 2012). Hence, agricultural innovation requires a deeper understanding of not only the role of innovation actors and their actions and interactions within innovation processes but also the social-ecological dimensions of innovation (de Boon et al., 2022).

This paper presents a contextual case study of agricultural innovation in Mali, West Africa. Agricultural innovations in Mali have experienced similar challenges to previous examples such as the Green Revolution in Asia and maize production in Kenya. Between the 1960s and 1980s, Sub-Saharan Africa (SSA), including Mali, suffered from prolonged periods of droughts and famines, which prompted donors to provide aid and funding support for agricultural innovation. Innovations were driven through pathways or mechanisms that were exogenous to the system; where key agricultural innovations were financed through external funders, developed by specialists or researchers, distributed by agricultural extension services, and finally adopted by producers (Knickel et al., 2009). Examples of such exogenously developed innovations include improved maize and rice varieties, crop inputs such as crop fertilizers and pesticides, early maturing varieties, etc. (Davies, 2016). However, few studies also highlight alternate pathways or mechanisms that were more endogenous to the system. Farmers formed local 'innovation platforms' (Pamuk et al., 2014) that developed innovations that were more widely adopted, to enable farmers to adapt to long-term climate variability and drought (Mortimore, 2010; Nyong et al., 2007). These innovations closely aligned with the dynamic, non-linear pathways or mechanisms of innovation systems and were facilitated by social learning, community organization, and local adaptive knowledge transfer (Ajani et al., 2013; Nyong et al., 2007; Osbahr et al., 2008). Examples of such endogenously developed innovations include various crop management strategies such as the conservation of soil carbon content through zero tillage practices, mulching, use of organic manure, and agroforestry (Ajani et al., 2013).

However, despite a significant increase in cereal production since the 1990s (Kelly et al., 2013), these innovations have not been successful in combating food insecurity in the region (Davies, 2016). Several explanations have been offered for the increase in food insecurity despite an increase in cereal yield and production and a decrease in income inequality in Mali, including low innovation uptake in the case of exogenous innovations (Elliott, 2010; Pamuk et al., 2014; Minot, 2008) or the extremely localized nature of endogenous innovations with limited opportunities for scaling and diffusion (Mortimore, 2010; Nyong et al., 2007). The food security paradox in Mali (Cooper & West, 2017) highlights the need to understand how innovation systems operate across scales, particularly focusing on the mechanisms that drive innovation outcomes within the social-ecological system. The term 'mechanism' has been used in several different ways across disciplines, sometimes as a 'causal process' and sometimes as a representation of the necessary elements of a process that produces a phenomenon of interest (Hedström & Ylikoski, 2010). In this paper, we adopt the sociological definition of mechanisms as a set of entities with distinct properties, roles, actions, and interactions with one another that bring about change based on the qualities of the entities and their spatial and temporal organization (Hedström, 2005).

We present an empirically informed, stylized agent-based model (henceforth, Ag-Innovation model) that includes both social and ecological dimensions of innovation processes. In the model, food security and income inequality outcomes emerge from (inter-)actions of innovators and farmers in their social-ecological environments. Our research questions were: i) How does the inclusion of social-ecological interactions in the model affect food security and income inequality outcomes? ii) How do exogenous and endogenous mechanisms influence food insecurity and income inequality outcomes? iii) What are the conditions under which exogenous and endogenous mechanisms would improve food security? We intended the Ag-Innovation model as a tool to conduct thought experiments for the development and testing of model hypotheses and generate an understanding of the behavior of agricultural innovation systems. The model is partly stylized and informed by both theory and empirics. We compare the model outcomes from simulations from two different model structures (i.e., the two innovation mechanisms), and assess the results relative to a theoretical maximum of food security or income inequality. We call it a thought experiment because of the theoretical nature of our exploration, albeit one that is informed by empirical data. The use of key theories of innovations, substantiated by evidence of how agricultural innovation processes operate in Mali and sub-Saharan Africa in general, allows us to develop reasonable confidence in the operationalization of the two distinct innovation mechanisms in the model. We urge readers to note that in the real world, the two mechanisms can and do occur simultaneously, but we restrict this study to an exploration of the two mechanisms separately in order to understand the consequences of each mechanism in isolation.

The paper is organized in the following ways: Section 2 highlights the model development process, including the incorporation of theories for exogenous and endogenous mechanisms of innovation, identification of key innovation actors and interactions, and the use of the Social-Ecological Action Situations Framework (SE-AS) (Schlüter et al., 2019) as a boundary object and diagnostic tool for integration of social and ecological dynamics within the model. Section 3 elaborates on the design and structure of the Ag-Innovation agent-based model, including agents and ecological entities and their attributes, model environment, and agent actions and interactions. Section 4 comprises the model analysis, including model runs, outcomes, and scenario experiments. Section 5 highlights model results followed by a discussion on three of the key insights drawn from the scenario experiments (Section 6), and the study's limitations (Section 7) and conclusion (Section 8).

2. Model development

Models that aim to theorize mechanisms underlying social-ecological systems need an approach that takes relevant contextual factors into account while still generating insights that hold across several similar cases. Such models need to be empirically embedded (Boero & Squazzoni, 2005) while representing stylized insights that are valid across cases. Models that are stylized but empirically grounded can serve as effective thought experiments in SES (Schlüter, Müller et al., 2019). Our model is empirically informed and structurally realistic but stylized model (Schlüter, Müller et al., 2019), in that we capture relevant contextual social-ecological factors within agricultural innovation systems in Mali while formalizing distinct exogenous and endogenous innovation mechanisms that can generate insights applicable across several similar cases. Model development involved an iterative process of drawing from theory and empirical evidence to construct a model that incorporated a sufficient level of empirical detail and generated outcomes comparable to real-world observations. The process of development of the conceptual framework of the model involved, first, the identification of key theories and empirical insights that would guide the structure of the model, including the identification of key actors (agents), their characteristics, behavior, and actions and interactions, followed by an iterative process of diagnosis of social-ecological elements and their interactions to ensure that the model adequately integrates both social and ecological dynamics in the innovation mechanisms. In the following sections, we highlight the process of combining theory with empirics that guided the model design and the application of the Social-Ecological Action Situation (SE-AS) framework (Schlüter, Haider et al., 2019) as a boundary object and diagnostic tool to facilitate the integration of SES dynamics within the model.

2.1 Theory

The formalization of the two innovation mechanisms within the ABM was an iterative process of distillation from theory and empirics to its most relevant elements and structures. We reviewed various theories of innovation development, dissemination, and diffusion and found four main theories that guided the formalization of innovation mechanisms within the model. We elaborate on these theories in Sections 2.1.1 and 2.1.2 below.

2.1.1. Exogenous mechanism

Early conceptualizations of innovation processes were influenced by the field of economics and organizational research and were instrumental in developing the national agricultural innovation development and dissemination channels in developing countries. The theory that informed the design of the exogenous mechanism of innovation were the theory of innovation (Schumpeter & Nichol, 1934), the technological push and pull theory (Schmookler,1966; Scherer, 1982), and the theory of innovation diffusion (Rogers et al., 2014). These theories assumed rational decision-making of innovation adopters and conceptualized innovation as a process of invention through research for technological improvement. The theory of technological push and pull viewed innovation as an interplay of knowledge-driven technology-push and market-driven demand-pull for innovation development. The theory of innovation diffusion focused on the spread of innovations through communication channels where innovations are adopted first by a small minority of early adopters and then followed by the early majority, late majority, and finally laggards. These theories collectively informed the implementation of agricultural innovation where external funds would be allocated to national and international agricultural research and development organizations to develop science-based agricultural technologies that would be then marketed through agricultural extension to farmers to ensure ‘delivery’ and subsequent adoption and diffusion of such solutions among users.

Based on our theoretical review, we identified three key actors within the exogenous mechanism of innovation: external innovators (who represent national and international agricultural research organizations and companies involved in agricultural development), early adopters (who represent larger producers who directly adopt innovations from external innovators) and late adopters (small and medium producers who indirectly adopt innovations through social learning from other farmers). We found three main interactions between these actors: 1) interactions between donors and external innovators including capital allocation and innovation goal formation leading to innovation development; 2) interactions between innovators and producers leading to innovation dissemination, and 3) interactions between producers including social learning leading to innovation diffusion. Table 1 summarizes the theories, actors, and interactions represented in the model.

2.1.2. Endogenous mechanism

Critiques of the exogenously driven innovation promoted by development and aid agencies refocused attention on endogenous, locally driven innovation (see Matthews, 2017; Röling, 2009). The theory that informed the design of the endogenous mechanism of innovation was the spiral model of social innovation where innovation is seen as collective action between actors towards a common goal. Within this theoretical conceptualization, innovation is spread through the ‘formation and re-formation of cooperating groups,’ resulting in an expansion of a variety of products and processes (Tapsell & Woods, 2008). Within the spiral model of social innovation, the actors within an innovation system are seen as engaging in experimentation, exploration, learning, and adaptation to respond to a changing environment. Innovation occurs as an emergent outcome through feedback between individual micro-level producers and meso-level collectives (Hounkonnou et al., 2012). These circular and iterative interactions commonly result in consensus building over individualist, linear approaches (Matthews, 2017) where the goal of the decision-maker is to achieve social consensus as opposed to individual gain (Mangaliso, 2001).

We identified three key actors within the endogenous mechanism of innovation: collective innovators (who represent farmer cooperatives and collective groups who test and experiment with agricultural techniques), early adopters (who represent smaller producers who directly adopt innovations), and late adopters (larger producers who indirectly adopt innovations through social learning from other farmers). We found two main interactions between these actors: 1) interactions between collectives and producers where collectives form innovation goals, develop innovations and interact with early producers leading to innovation dissemination for innovation adoption; and 2) interactions between producers through the collective formation, capital pooling leading to innovation development and innovation knowledge sharing leading to innovation diffusion (see Table

1). Note that all the interactions highlighted in these different innovation mechanisms are social interactions, indicating that these theories focused exclusively on interactions with the social entities within innovation.

Table 1: Specific actors, their characteristics, and their social interactions in the Ag-Innovation model.

	Exogenous mechanism	Endogenous mechanism
Theory	Theory of Innovation Technology push-pull theory Theory of Innovation diffusion	Spiral theory of innovation diffusion
Actors	External Innovators Early adopters *(large producers)* Late adopters *(small and medium producers)*	Collective Innovators Early adopters *(small and medium producers)* Late adopters *(large producers)*
Social Interactions	*Donors-Innovators:* Donors interact with innovators through capital allocation and the formation of innovation goals for innovation development. *Innovators-Producers:* Innovators interact with early producers through innovation dissemination for innovation adoption. *Producers-Producers:* Early adopter producers interact with late adopter producers through innovation knowledge sharing for innovation diffusion.	*Producers-Producers* Producers interact with producers through collective formation and capital pooling for innovation development. *Producer-Collectives:* Collectives interact with producers in the network to form innovation goals. Collectives interact with early producers through innovation dissemination for innovation adoption. *Producers- Producers:* Early adopter producers interact with late adopter producers through innovation knowledge sharing for innovation diffusion.

2.2. Diagnosis of social-ecological interactions in agricultural innovation systems

We aimed to formalize innovation as a social-ecological phenomenon rather than just as a social phenomenon. However, as we noted above in Table 1, initial formalizations of the model were biased toward social interactions between the innovation actors with no social-ecological or ecological interactions. This occurred largely because existing theories focus solely on social interactions between actors within the innovation system (see Table 1). The expansion of innovation as a social-ecological phenomenon involved an iterative process of uncovering additional ecological variables that influence innovation processes, beyond social interactions of invention development, adoption, and diffusion. We used the framework of linked social-ecological action situations (SE-AS) (Schlüter, Haider et al., 2019) to set system boundaries and identify the key social as well as ecological entities and their interactions within social-ecological innovation. We also used the SE-AS framework as a diagnostic tool to ensure adequate representation of both social and ecological dynamics within the model.

The SE-AS framework was originally developed to understand the actions and interactions between the social and ecological entities that lead to processes of emergence of complex social-ecological phenomena such as regime shifts, traps, and sustainable resource use (Schlüter et al., 2014; Schlüter, Haider et al., 2019). This framework has been used as a tool to capture interactions that are hypothesized to have generated a social-ecological phenomenon of interest and support a process of developing hypotheses about configurations of action situations that may explain an emergent social-ecological phenomenon (Schlüter, Haider et al., 2019). These interactions can be either social (between human entities), social-ecological (between human and non-human entities), or ecological (between non-human entities). We identified three social-ecological and ecological interactions that were critical dynamics that needed to be incorporated into the model to ensure the assessment of innovations as a social-ecological phenomenon (Fig. 3 and Fig. 4). These additional interactions include: 1) donor-innovator interactions where climate risks trigger donors to allocate foreign aid to innovators; 2) producer-farmland interactions where climate risk perception influences producers crop choices and assessment of production history leads to the formation of beliefs on the need for innovation and the type of innovations desired by the producers; and 3) crop-soil interaction where the type of innovation adopted regulates soil fertility and crop diversity. Table 2 highlights the additional entities and social-ecological interactions in the model. Figures 1 and 2 are the visual representation of SE-AS interactions in exogenous and endogenous mechanisms in the Ag-Innovation model respectively. The social-ecological interactions are included in the Ag-Innovation model through a series of computational algorithms that estimate climate risk perception, crop selection, and innovation belief and desire formation. Similarly, the emergent SES phenomena (food security and income inequality) are the model outcomes in the ABM. Details of the formalization of these interactions are highlighted in the overview of the Ag-Innovation model in following section 3 as well as the ODD protocol in Supplementary Material A.

Table 2: Additional entities and social-ecological interactions in the Ag-Innovation model for both endogenous and exogenous mechanisms

Ecological entities	Interaction Type	Interactions in the model
Farmland Crop Soil	Social-Ecological interactions	*External drivers (e.g., climate change, droughts)* Climate change drives changes in temperature and precipitation patterns and climate risks such as droughts, excessive rainfall, and extreme heat. Climate risks trigger donors to allocate foreign aid to innovators. *Producers – Farmlands* Producers interact with farmland through crop selection and cultivation based on climate risk perception. Producers interact with farmland through the formation of innovation beliefs and desires.
	Ecological interactions	*Crop – Soil* Crop interacts with soil through the regulation of soil fertility.

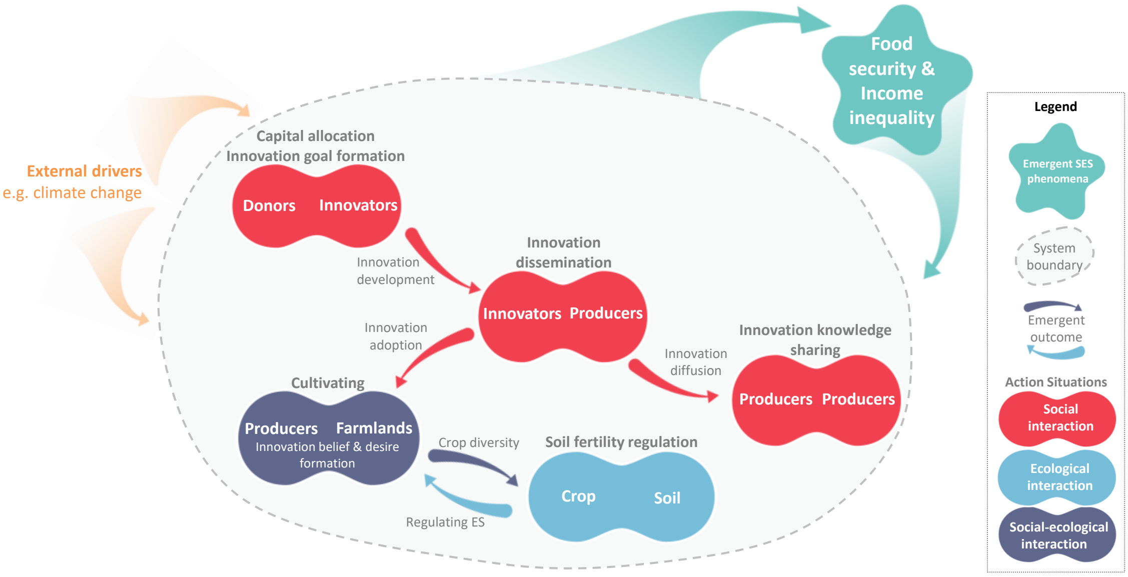

Figure 1: Social-ecological representation of the configuration of social-ecological (dark blue), social (red) and ecological action situations (light blue) different actors and ecological entities in the exogenous mechanism. The configuration of action situations influences each other through emergent outcomes (arrows) that jointly generate food security and income inequality at a system level (green figure as the emergent SES phenomena of interest).

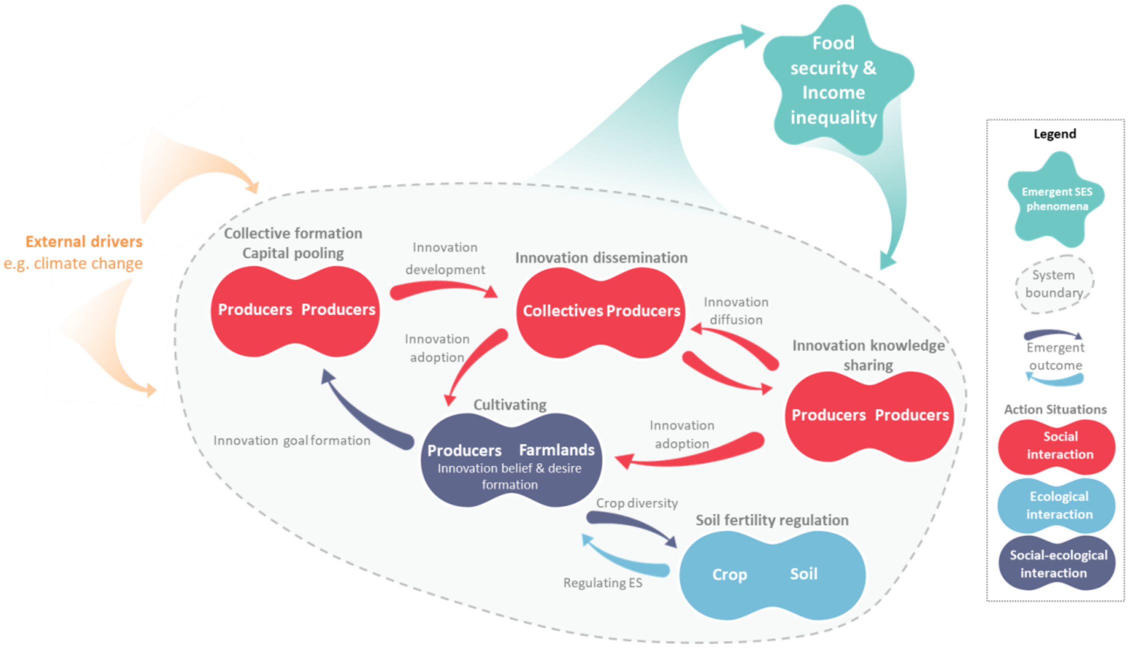

Figure 2: Social-ecological representation of the configuration of social-ecological (dark blue), social (red) and ecological action situations (light blue) different actors and ecological entities in the endogenous mechanism. The configuration of action situations influences each other through emergent outcomes (arrows) that jointly generate food security and income inequality at a system level (green figure as the emergent SES phenomena of interest).

3. Ag-Innovation Model: Overview

In this section, we provide an overview of the model, a detailed description of the Ag-Innovation model can be found in the ODD protocol (Grimm et al., 2006) in the Supplementary Material.

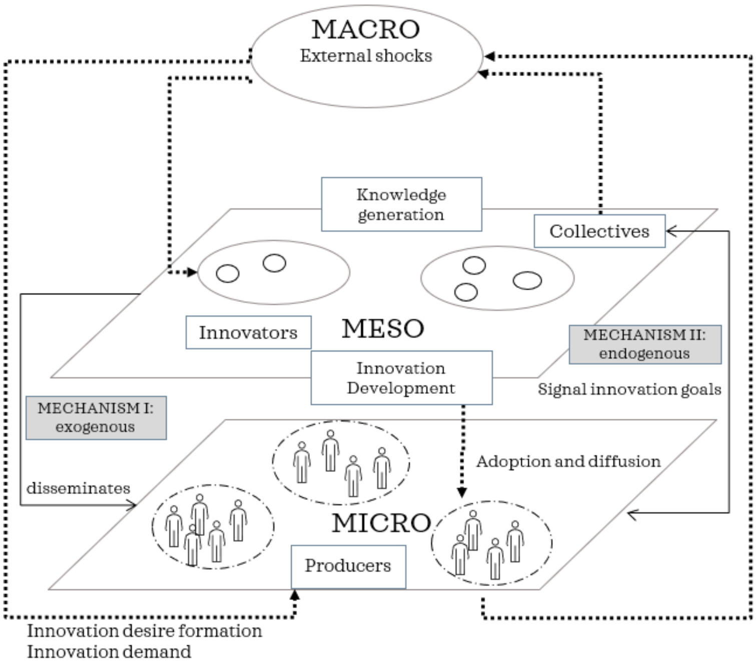

Figure 3: Visualization of cross-scalar interactions in Ag-Innovation model.

The Ag-Innovation model captures three key processes of innovation: innovation development, innovation adoption, and innovation diffusion, while incorporating social-ecological interactions within each of these processes. These dynamics are essential for a system's perspective of how innovations operate across scales and influence or are influenced by various innovation actors (see Figure 3). Cross-scalar interactions in the model occur through the signaling of producers operating at the micro-scale and innovators operating at the mesoscale. Innovator agents (external innovators and collective innovators) are involved in innovation development and dissemination while producer agents are involved in innovation adoption and diffusion. The essential dynamics within innovation development include capital allocation, innovation goal formation, innovation development, and dissemination to potential adopters. The dynamics within innovation adoption include climate risk perception, crop production estimation, formation of innovation beliefs/desires, innovation adoption, and innovation diffusion.

3.1. Model Structure

The model environment for the Ag-Innovation model represents the entire country divided into four key agroclimatic zones (Figure 4). The four zones exist in a gradient with the extremely arid sandy Sahelian and Saharan zones in the North (with annual precipitation less than 200 mm) to the more tropical Sudanian-savanna regions in the South (with annual precipitation around 1000-1200 mm) (Waldman & Richardson, 2018). In the model, these are represented as patches divided into four climate zones (Zone 1-4) with respective attributes of temperature and precipitation, soil fertility, and crops grown within which agents reside. The Ag-Innovation model consists of three key agents: external innovators, collective innovators, and producers. Collective innovators represent farmers' associations or groups in farmer field schools who collectively test and experiment to develop innovations that may be suitable for the local context. The external innovators represent external agricultural entities such as international agricultural development organizations or private agencies that are funded by external or foreign aid for developing agricultural innovations. Producers are farmers who own land, cultivate crops, form beliefs and desires about innovation, and adopt innovations. Table 3 outlines the agent attributes and their description in the Ag-Innovation model.

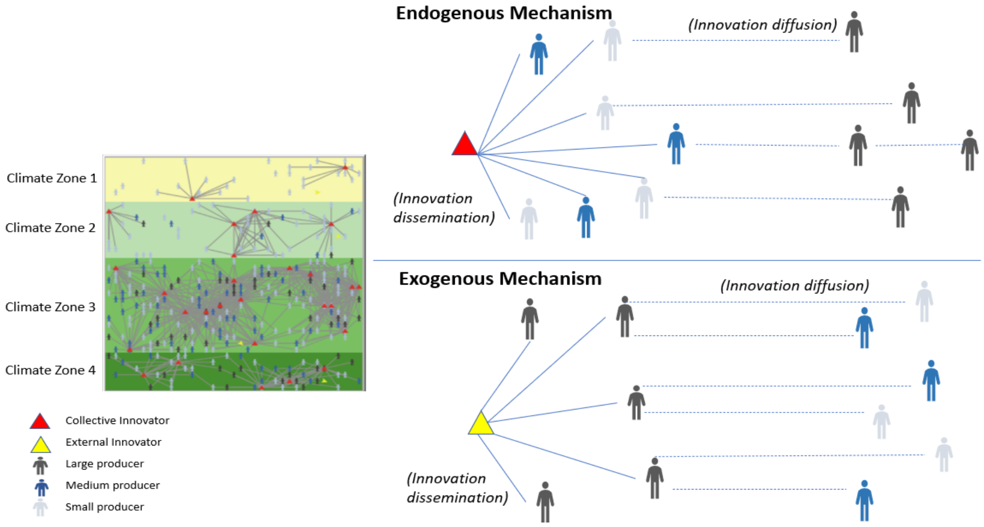

Figure 4: Model environment representing climate zones and distribution of agents.

The model explores two distinct mechanisms of innovation (exogenous and endogenous) with different configurations, networks, roles, and actions of innovator and producer agents (Figure 4). In the exogenous mechanism of innovation, innovator agents are external innovators who are directly connected with early adopters (in this case, large producers) for innovation dissemination. Late adopters (small and medium producers) interact with early producers to spread innovation adoption. In the endogenous mechanism of innovation, innovators are collective agents who are directly connected with early adopters (small and medium producers) for innovation dissemination. Late adopters (large producers) interact with early producers to spread innovation adoption. In both exogenous and endogenous mechanisms, producers interact with ecological entities, for example, their farmlands, crops, and soils through climate risk perception that guides crop selection, formation of innovation beliefs and desires, and innovation adoption. Here, belief is based on the assessment of the producer's need for innovations based on the type of crops grown, crop production, and soil fertility. Desires are the type of innovations the producer needs, including 'production,' 'stability,' or 'conservation' oriented innovations[1].

The key outcome variables in the model are food security, income inequality, and adoption rates of different types of innovations (production, stability, and conservation) over time. Food security is an outcome that shows the proportion of producer agents who are food secure (i.e., whose food production is equal to or higher than their household food requirement). Surplus food is sold for income that increases capital owned by producers. Income inequality is an outcome that shows the Gini coefficient of capital distribution among producer agents which represents the degree of inequality in a distribution. A Gini coefficient of 0 expresses perfect equality while a Gini coefficient of 1 expresses maximum inequality among values. We ran the model over 200 times, each run with 100-time steps. Each time step represents an agricultural production year.

Table 3: Agent attributes in the Ag-Innovation model.

Agent	Attribute	Type	Description
Producers	landsize	static	Size of farmland
	farmtype	static	Type of farmer (small, medium, large)
	soilfertility	dynamic	Index that represents soil fertility
	householdsize	static	Number of members in the household
	adoptertype	static	Type of adopter (early adopter, late adopter); changes with innovation mechanism
	capital	dynamic	Capital owned
	cropchoice	dynamic	Choice of crop (rice, wheat, maize, or millet)
	cropproduction	dynamic	Amount of crop produced
	food-requirement	dynamic	Amount of food required by the agent's household in a year
	food-secure	dynamic	Binary variable (True if crop production is higher than food requirement, False if crop production is lower than food requirement)
	innovation-needed	dynamic	Binary variable (True or false)
	innovation-desire	dynamic	Type of innovation needed by agent (production, stability, or conservation)
	adoption-capacity	static	Capacity of agent to adopt innovation (range 0-1 based on farm type)
	innovation-adopted	dynamic	Type of innovation adopted (production, stability, or conservation)
	adoption-status	dynamic	Binary variable, whether the agent adopted an innovation or not (True or False)
Innovators	innovator-type	static	Type of innovator (external innovator or collective); changes with innovation mechanism (endogenous or exogenous)
	innovation-capital	dynamic	Capital endowment of innovator
	innovation-goal	dynamic	Type of innovation that the innovator wants to develop (production, stability, or conservation)
	innovation-available	dynamic	Type of innovation developed by the innovator (production, stability, or conservation)
	knowledge-efficiency	dynamic	Index that represents knowledge of what kind of innovation is needed by producers
	capital-efficiency	dynamic	Index that represents capital as proxy for infrastructure development (capital available /capital needed)

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[1] Production-oriented innovations represent innovations such as improved seed varieties and fertilizers that lead to an increase in crop yield. Stability-oriented innovations are innovations such as climate tolerant crop varieties that lead to stabilization of crop yield. Conservation-oriented innovations are innovations such as no-tillage practices, composting, and intercropping that lead to an increase in soil fertility.

3.2. Model calibration

We used a combination of qualitative and quantitative empirical data to calibrate the model including the modelling environment, agent distribution, agent attributes, and decisions to replicate our stylized model as close to the relevant agricultural realities of Mali as possible. The calibration of climatological parameters in the model such as sowing, growing and maturing temperatures, and precipitation within the four climate zones were based on meteorological data from the World Meteorological Organization (WMO). Data was processed to compute the average monthly temperature and precipitation of weather stations for the period 1961-1990 in each zone. Sowing, growing, and maturing season temperature and precipitation were calibrated using mean monthly value for months May to July, August to September, and October to November respectively. Estimation of crop yield (for maize, sorghum, millet, and rice) was based on a series of four regression equations calculated for Mali using national-level meteorological data for period 1961-1990 (see Sanga, 2020). Calibration of agent distribution, land size, crops grown, household size, and per capita food consumption (maize, millet, rice, and sorghum) was based on secondary data (INSTAT Mali data portal, https://mali.opendataforafrica.org/; Batana & Cockburn, 2018; Sanga, 2020). The model functionalized climate risk assessment of agents and subsequentcrop choice decisions based on insights from Sanga et al. (2021) that assessed agricultural decision-making under climate risk and uncertainty using participatory role-playing board games. Further details of the model calibration can be found in Section 6 of the ODD protocol in Supplementary Material A.

3.3. Agent actions

Producers perform nine actions: i) assess climate risk; ii) make crop choice for cultivation; iii) estimate expected crop production; iv) assess innovation need; v) develop innovation desire; vi) adopt innovation (directly from innovator/collective agents by early adopters and social learning for late adopters); vii) assess crop production; viii) allocate produce for household consumption and selling; and ix) allocate a share of available capital to collectives (see Table 4 for details). The innovator agents (external innovator in case of exogenous and collective in case of endogenous mechanism) perform four actions: i) update capital for innovation, ii) set innovation goal, iii) develop innovation and iv) disseminate innovation to early adopters (see Table 5 for details). Figure 5 highlights a simplified illustration of the actions of the producers and innovators/collectives and the interactions between meso and micro levels. A detailed flowchart of agent actions can be found in the ODD protocol in Supplementary Material B.

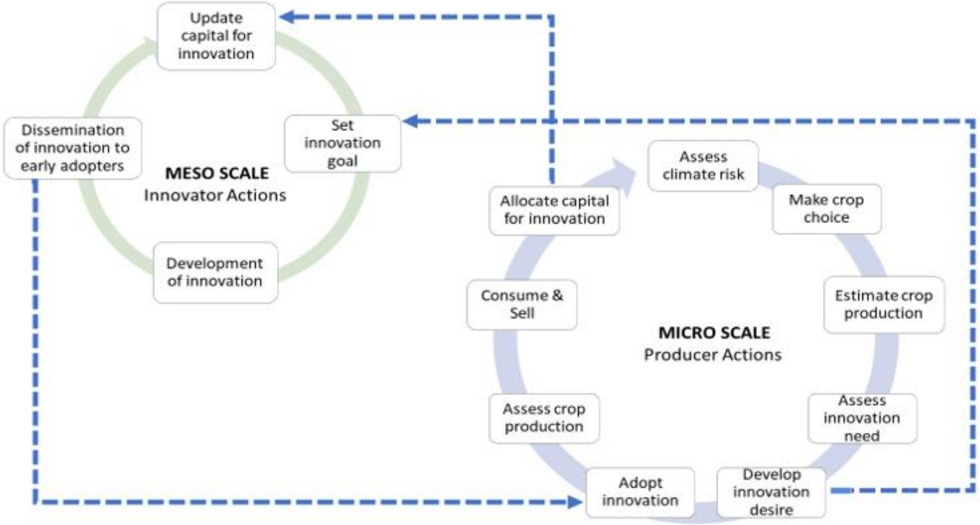

Figure 5: Meso and micro-level agent actions and their linkages for both exogenous and endogenous models (dashed blue line).

Table 4: Actions of producer agents (further details can be found in Supplementary Material A, ODD protocol Section 8)

Agent actions	Model Procedure
Climate risk assessment	▪ Producer agents calculate the difference between temperature and precipitation (sowing, growing, and maturing seasons) values at time step with the mean temperature and precipitation (sowing, growing, and maturing seasons) for the previous 10 time-steps. ▪ The difference from mean is used to estimate climate risk (early, mid-season, and terminal drought, excessive rainfall, and extreme temperature) at a particular time step.
Crop choice	▪ Agents select crops sorghum or millet in case of early season drought, maize and millet during midseason or terminal drought; millet sorghum or rice in case of excessive rainfall; or sorghum in case of extreme temperature.
Crop production estimation	▪ Producer agents estimate crop yield and production based on climate variables (temperature and precipitation in sowing, growing, and maturing seasons)
Innovation belief and desire formation	▪ Agents estimate soil fertility at their patches, estimate crop production at the current time step as well as the mean and standard deviation of past crop production history for the previous 10 timesteps. ▪ If soil fertility is lower than a certain threshold, the agents set their innovation belief as true and innovation desire as 'conservation'. ▪ If the agent has a negative production gap between current crop production and mean of previous 10 time-steps production history, the agents set their innovation belief as true and innovation desire as 'production'. ▪ If producer agents have a high standard deviation in crop production history (indicating high crop production variability), agents set their innovation belief as true and innovation desire as 'stability'.
Innovation adoption	▪ Early adopters adopt innovation if available innovation matches with their innovation desire. ▪ Late adopters adopt the most popular innovation adopted by the early adopters in their vicinity if it matches with their innovation desires.
Crop production assessment	▪ If innovation adopted is ¨production¨, crop yield increases by an amount proportional to the innovation efficiency and soil fertility decreases. ▪ If innovation adopted is ¨conservation¨, crop yield increases by an amount proportional to the innovation efficiency and soil fertility increases. ▪ If innovation adopted is ¨stability¨, crop yield is maintained by an amount proportional to the innovation efficiency.
Consumption and selling	▪ Producer agents calculate household food requirements. If food production is greater than food requirement, agents set their status food secure and sell excess food. Otherwise, producer agents set status food insecure.
Capital allocation	▪ Endogenous mechanism: Early adopter producer agents allocate a share of their capital to the innovation capital of the collective agent. ▪ Exogenous mechanism: Producer agents do not allocate capital to external innovator agents.

Table 5: Action of innovator agents

Agent Actions	Model Procedure
Innovation goal setting	▪ Exogenous mechanism: External innovators randomly select innovation goal between production, stability, and conservation. ▪ Endogenous mechanism: Collective innovator selects the innovation most desired by the early adopter producers in their network as the innovation goal.
Innovation development	▪ Collective/external innovators agents compute the innovation efficiency which is a function of knowledge efficiency of the innovator (representing knowledge of what kind of innovation is needed by producers) and the capital efficiency (capital available to innovator/capital needed by innovator)
Innovation capital updation	▪ Exogenous mechanism: External innovators update innovator capital based on capital allocated through foreign aid capital. ▪ Endogenous mechanism: Collective innovators update innovator capital based on the pooling of capital allocated by producers connected within their network

4. Model Analysis

4.1. Design of experiments

As we highlighted in previous sections, we aimed to conduct an exploratory analysis of the Ag-Innovation model to answer three key questions:

i) Does the inclusion of social-ecological interactions in the model change the effect of the two mechanisms on food security and income inequality?
ii) How do exogenous and endogenous mechanisms influence food security and income inequality?
iii) What are the conditions under which food security and income inequality will improve?

To answer the first question, we designed a set of four model experiments that would allow us to answer these questions. In experiments 1 and 2, we included only social interactions in the innovation model. Experiment 1 explored the social endogenous mechanism (S-Endo) while experiment 2 explored the social exogenous mechanism (S-Exo). In experiments 3 and 4, in addition to social interactions, we included social-ecological interactions in the model, including climate risk perception, moderate increase in temperature, moderate decrease in precipitation, and regulatory ecological feedback on soil fertility from innovation adoption. Experiment 3 explored the social-ecological endogenous mechanism (SE-Endo) while experiment 4 explored the social-ecological exogenous mechanism (SE-Exo). A comparison of experiments 1 and 3 and experiments 2 and 4 allowed us to assess if the inclusion of social-ecological interactions in the innovation model would have any influence on food security and income inequality outcomes. Table 6 provides details of the design of experiments in the Ag-Innovation model.

Table 6: Design of Experiments in the Ag-Innovation model

Model Variables	**Innovation as a social phenomenon** (Experiment 1: Endogenous) (Experiment 2: Exogenous)	**Innovation as a social-ecological phenomenon** (Experiment 3: Endogenous) (Experiment 4: Exogenous)
Network width	Included	Included
Innovator density	Included	Included
Capital allocation	Included	Included
Climate risk perception	Not included	Included
Moderate increase in temperature	Not included	Included
Moderate decrease in precipitation	Not included	Included
Ecological feedback (Effect of innovation adoption on soil fertility)	Not included	Included

To answer the second and third questions, we developed experiments 5, 6, and 7 that explored model outcomes of food security and income inequality under scenarios of no innovation, exogenous innovation, and endogenous innovation, respectively. Comparing model outcomes of experiments 5 and 6 allowed us to explore if an exogenous mechanism would lead to higher food security and income inequality. Comparing model outcomes of experiments 5 and 7 allowed us to explore if endogenous mechanism would lead to lower food security and income inequality. We also conducted a sensitivity analysis using the BehaviorSpace tool in NetLogo (version 6.2.2) (Wilensky, 1999) through parameter tuning by repeated execution, i.e., varying one input parameter at a time while keeping the remaining parameters unchanged (update-threshold, second chance-interval; see Remondino and Correndo, 2006 for details) to find the conditions under which endogenous and exogenous innovation mechanisms would be effective in improving food security and income inequality outcomes. See Table 7 for the values explored for the sensitivity analysis.

Table 7: Experimental set-up for sensitivity analysis.

Scenarios	Variable	Value explored	Increment
Experiment 5: No innovation Experiment 6: Exogenous Innovation Experiment 7: Endogenous Innovation	network-radius	[1,10]	1
	innovator-density	[0.01, 0.1]	0.01
	foreign-aid	[100000, 1000000]	100000
	capital allocation-rate	[0.1,1]	0.1

4.2. Model Results

4.2.1. Inclusion of social and social-ecological interactions within innovation

Food security outcomes were lower in social-ecological innovation than in social innovation and income inequality outcomes were higher in social-ecological innovation than in social innovation for both exogenous and endogenous mechanisms (Figure 6 a and b). See summary statistics of the distribution of food security and income inequality outcomes in Table 8.

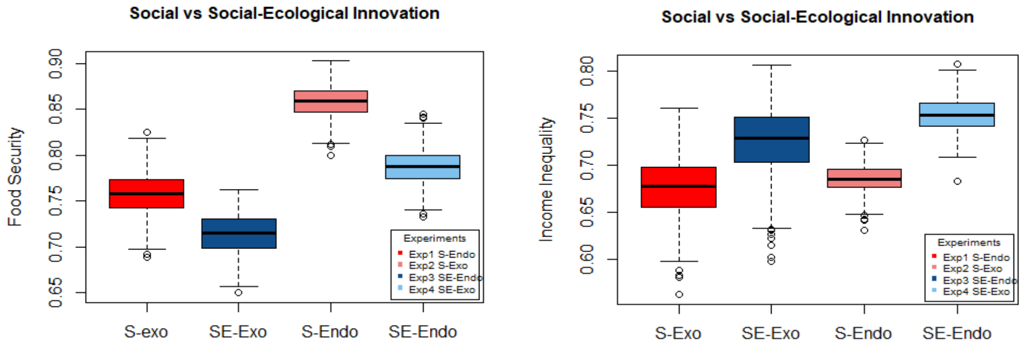

Figure 6: Model outcomes for Experiment 1-4 on a) food security and b) income inequality

Table 8: Summary statistics for the model outcomes for Experiments 1-4.

		Experiment 1 Endogenous social mechanism	Experiment 2 Exogenous social mechanism	Experiment 3 Endogenous social-ecological mechanism	Experiment 1 Exogenous social -ecological mechanism
Income Inequality	Min.	0.6310	0.5624	0.6833	0.5975
	1st Qu.	0.6764	0.6555	0.7418	0.7037
	Median	0.6854	0.6776	0.7534	0.7289
	Mean	0.6856	0.6753	0.7541	0.7257
	3rd Qu.	0.6957	0.6986	0.7661	0.7509
	Max.	0.7271	0.7607	0.8075	0.8064
Food security	Min.	0.7997	0.6886	0.7323	0.6498
	1st Qu.	0.8468	0.7424	0.7744	0.6987
	Median	0.8586	0.7576	0.7870	0.7146
	Mean	0.8583	0.7580	0.7868	0.7145
	3rd Qu.	0.8704	0.7731	0.7997	0.7306
	Max.	0.9024	0.8249	0.8451	0.7626

An independent samples *t*-test was conducted to compare if these differences in the distribution of model outcomes were statistically significant. The results indicated a significant difference between the means of food security outcomes for experiments 2 and 4 (exogenous social and social-ecological innovation) (t = 31.307, df = 993.15, p-value < 2.2e-16) as well as experiments 1 and 3 (endogenous social and social-ecological innovation) (t = 61.259, df = 977.54, p-value < 2.2e-16). Results also indicated a significant difference between the means of the income inequality outcomes for experiments 2 and 4 (t = -23.456, df = 990.23, p < 2.2e-16) as well as experiments 1 and 3 (t = -65.016, df = 963.47, p < 2.2e-16).

Model results showed that in all experiments, income inequality decreased with an increase in food security among producers (Figure 7 a-d). However, the relationship between income inequality and food security was stronger for both endogenous and exogenous social-ecological innovation (experiments 3 and 4) (Figure 7 c & d, slope: - 0.27 & -0.3, spearman coefficient rho: -0.28 & -0.18 respectively) than for endogenous and exogenous social innovation (experiment 1 and 2) (Figure 7 a & b, slope: - 0.15 & -0.16, spearman coefficient: -0.168 & -0.12).

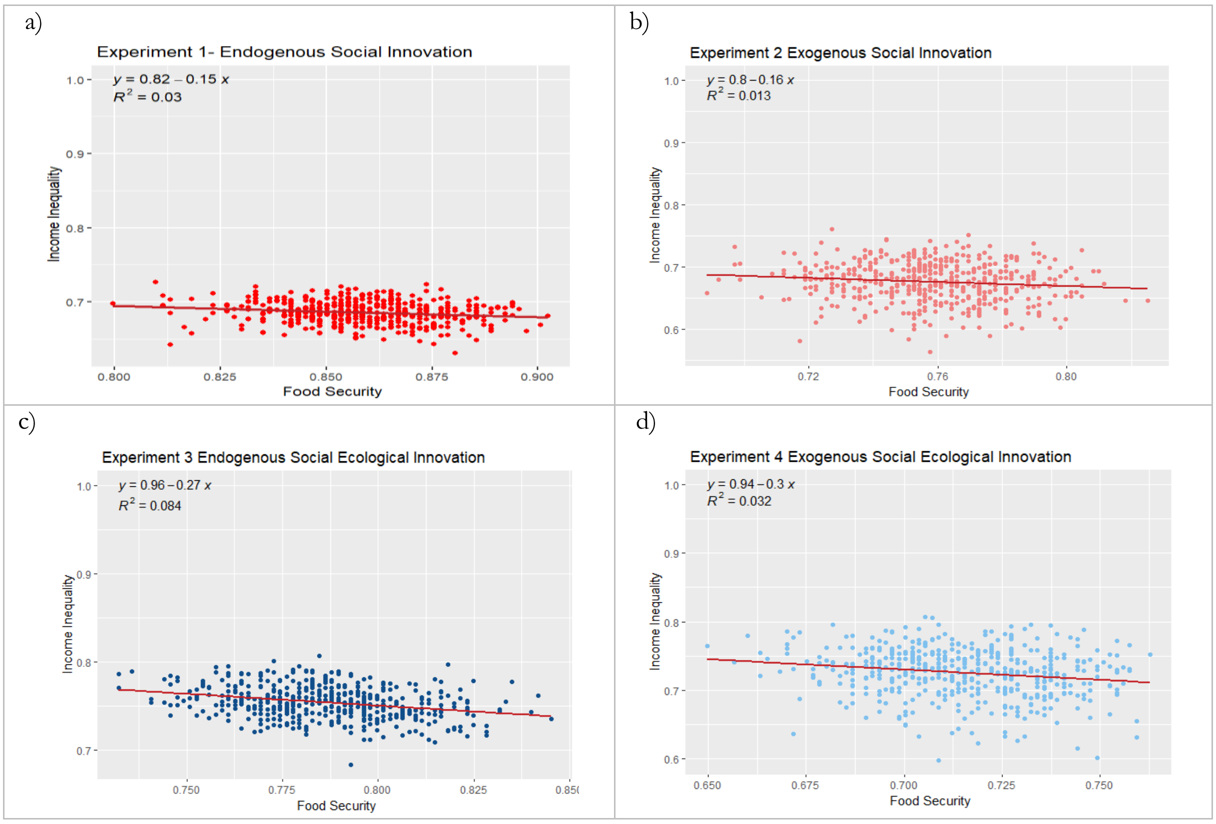

Figure 7: Income inequality outcomes for a) Experiment 1- Endogenous social innovation, b) Experiment 2- Exogenous social innovation, c) Experiment 3- Endogenous social-ecological innovation, and d) Experiment 4- Exogenous social-ecological innovation.

4.2.2. Exogenous and endogenous mechanisms of innovation

Exogenous mechanisms of innovation

Comparison of scenarios with no innovation and exogenous innovation (experiment 5 and 6) shows no difference in income inequality outcomes (mean: 0.7046, *p*-value = 0.8957) (see Table 9). Exogenous mechanisms demonstrated a greater variation in the results of income inequality than the model scenario with no innovation (Figure 8a). Exogenous innovation produced slightly higher food security and larger number of low-end outliers (mean = 0.70 and 0.73 respectively, *p*-value < 2.2e-16) and a larger number of low-end outliers (Figure 8b).

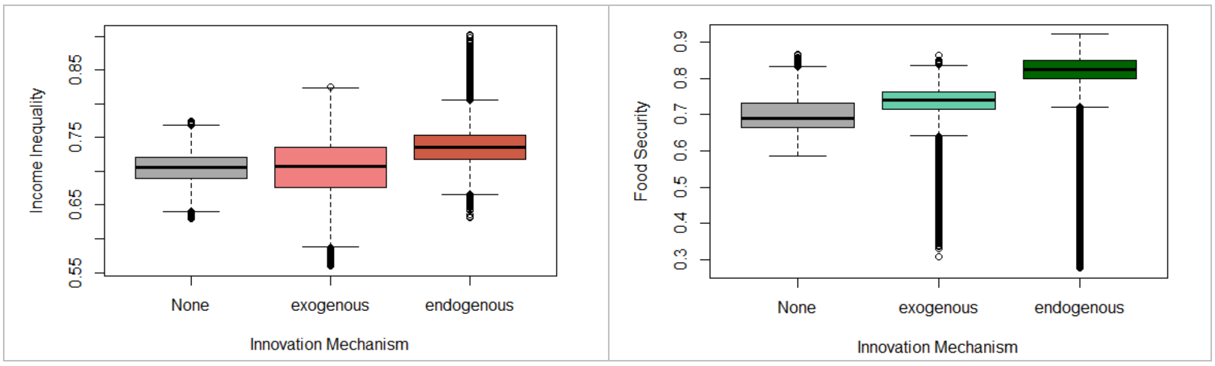

Figure 8: Comparision of model outcomes for a) Income inequality and b) food security.

Endogenous mechanisms of innovation

Comparison of scenarios with no innovation and endogenous innovation (experiments 5 and 7) shows that the endogenous innovation mechanism leads to higher income inequality (mean = 0.74 and 0.70 respectively, *p*-value < 2.2e-16 and food security (means 0.79 and 0.70 respectively, *p*-value < 2.2e-16). Food security outcomes in the endogenous mechanism show the presence of several higher-end outliers for income inequality and several lower-end outliers for food security (Figure 8b). See Table 9 for summary statistics for the model outcomes for scenarios of no innovation, exogenous innovation, and endogenous innovation, respectively.

Comparison of adoption rates of the different types of innovations (production, stability, and conservation) under the exogenous and endogenous innovation scenarios show that the endogenous innovation mechanism leads to a higher adoption rate of production-oriented innovations (Figure 9b), while the exogenous innovation mechanism leads to a higher adoption rate of stability-oriented innovations (Figure 9a). The adoption rate of conservation-oriented innovations is slightly higher for the endogenous mechanism than the exogenous mechanism. Overall, the rates of decline in food security (Figure 10a) and increase in income inequality (Figure 10b) are higher in both exogenous and exogenous mechanisms compared to the model scenario with no innovation.

Table 9: Summary statistics for the income inequality and food security model outcomes for scenarios: no innovation, exogenous innovation, and endogenous innovation.

Model outcomes	Mechanism	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Income inequality	None	0.6294	0.6889	0.7060	0.7047	0.7210	0.7743
	Exogenous	0.5592	0.6759	0.7078	0.7046	0.7352	0.8250
	Endogenous	0.6320	0.7178	0.7354	0.7390	0.7529	0.9021
Food security	None	0.5859	0.6633	0.6902	0.7003	0.7306	0.8653
	Exogenous	0.3081	0.7138	0.7391	0.7251	0.7626	0.8620
	Endogenous	0.2761	0.7980	0.8232	0.7984	0.8502	0.9209

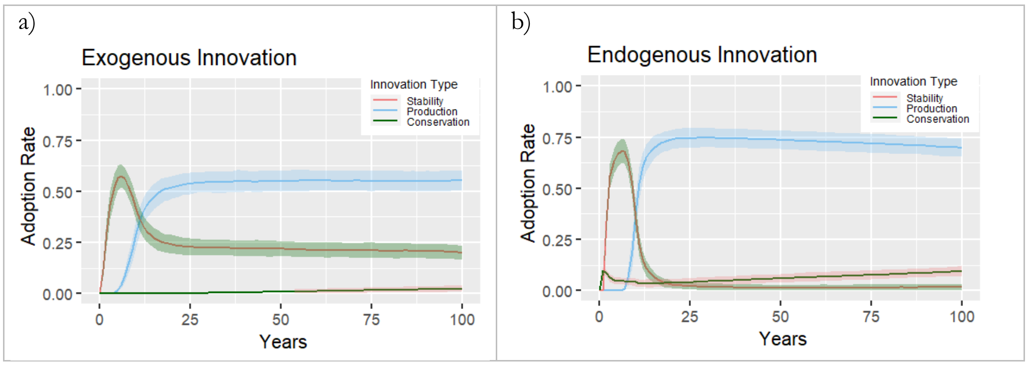

Figure 9: Innovation adoption rates over time for a) exogenous mechanism and b) endogenous mechanism.

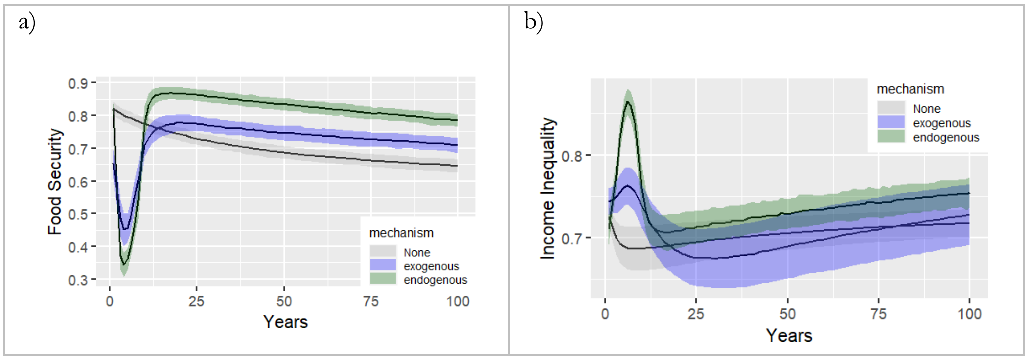

Figure 10: Model outcomes for exogenous, endogenous and no innovation mechanism for a) food security and b) income inequality over time.

4.2.3. Sensitivity Analysis Results

The results of the sensitivity analysis show that an increase in the rate of capital allocation increases income inequality in endogenous mechanism (Figure 11 d). Capital allocation rate does not affect food security outcomes for both endogenous and exogenous mechanisms (Figure 11 a and b). Foreign aid does not affect food security or income inequality outcomes for both endogenous and exogenous mechanisms (Figure 12 a,b,c,d). Food security increases with an increase in network radius for both exogenous and endogenous mechanisms (Figure 13 a and b). Income inequality decreases with an increase in network radius for endogenous mechanism (Figure 13 d). However, there is a tipping point in the exogenous mechanism where lower network radius leads to an increase in income inequality, but higher network radius leads to decrease in income inequality (Figure 13 c). Increase in innovator density leads to an increase in food security for both exogenous and endogenous mechanisms (Figure 14 a and b). Increase in innovator density leads to a decrease in income inequality for both mechanisms (Figure 14 c and d).

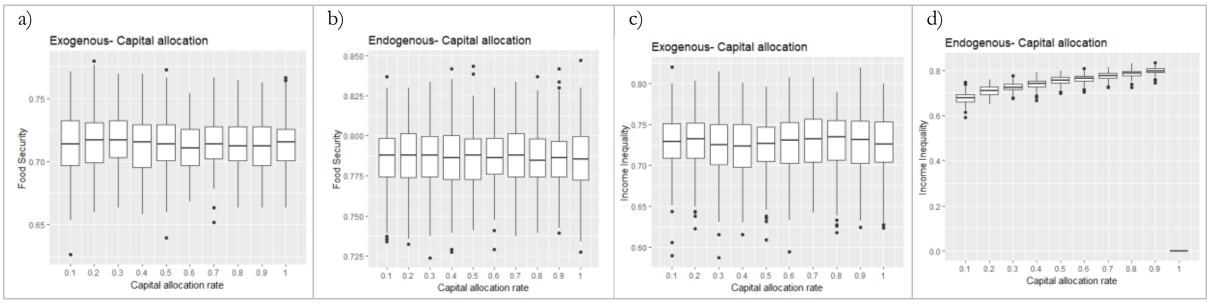

Figure 11: Effect of capital allocation rate on a) food security under exogenous mechanism, b) food security under endogenous mechanism, c) income inequality under exogenous mechanism, and d) income inequality under endogenous mechanism.

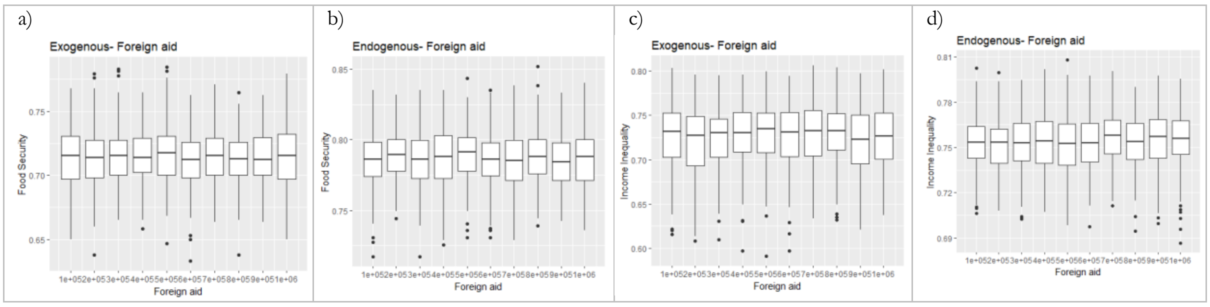

Figure 12: Effect of foreign aid on a) food security under exogenous mechanism, b) food security under endogenous mechanism, c) income inequality under exogenous mechanism, and d) income inequality under endogenous mechanism.

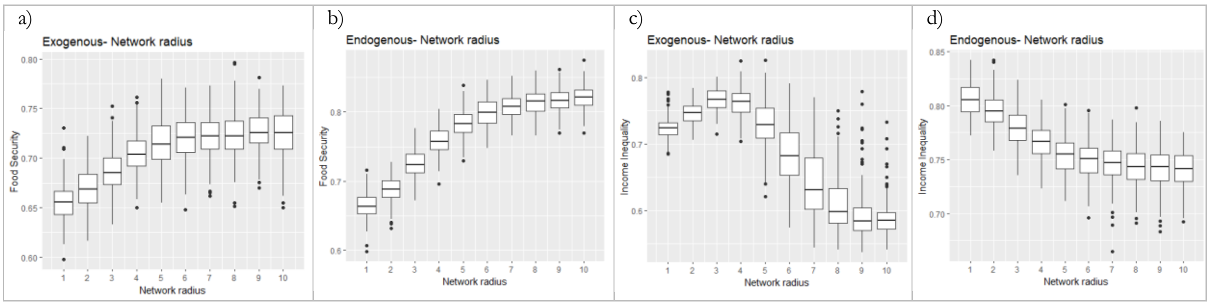

Figure 13: Effect of network radius on a) food security under exogenous mechanism, b) food security under endogenous mechanism, c) income inequality under exogenous mechanism, and d) income inequality under endogenous mechanism.

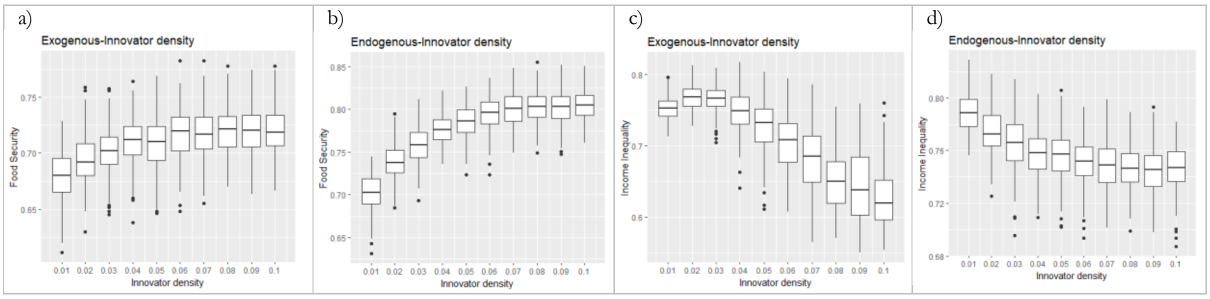

Figure 14: Effect of innovator density on a) food security under exogenous mechanism, b) food security under endogenous mechanism, c) income inequality under exogenous mechanism, and d) income inequality under endogenous mechanism.

5. Discussion

Models of social-ecological phenomena lie within a spectrum of theoretical, often abstract models and realistic, empirical models of specific case studies. While the former can lack links to the real world, making their results difficult to apply to real-world problems, the latter are very specific to a particular case with limited possibilities to generalize findings to other cases. In this study, we undertake an empirically driven, stylized modeling approach, where we iteratively combined theories of innovation processes with quantitative and qualitative empirical data and insights from a case of agricultural innovation in Mali. Our modeling approach does not aim to numerically replicate food security and income inequality in Mali as the model is stylized. Instead, we focus on the qualitative model validation through patterns generated by the model and use the model to explore our research questions through thought experiments. For example, the model generates an inverse relationship between food security and income inequality outcomes. This model result is supported and validated by evidence from observed patterns of food security and income inequality in Mali from previous studies. For example, Imai et al. (2015), who dynamically modeled the relationship between agricultural growth and income inequality in developing countries, found that agriculture-driven growth reduces inequality. Mali has seen a rise in agricultural growth and cereal production since the 1970s due to targeted agricultural policies that promote innovations and technologies that improve crop production (Giannini et al., 2017). Consistent with these observations, studies have noted a decreasing pattern of income inequality in Mali since the 1990s (Odusola et al., 2019). Learning from the exploratory scenario experiments analysis results, we draw three key insights relevant to agricultural innovation systems:

i) Incorporation of social-ecological interactions in the formalization of innovation influences model outcomes

Results from the experiments on the inclusion of social and social-ecological interactions in the model make a compelling case for the necessity of incorporating intertwined social-ecological dynamics in the assessment and modeling of agricultural innovation systems. The model scenario with the inclusion of social-ecological interactions showed a stronger inverse relationship between income inequality and food security outcomes than the model scenario with only social interactions. For both exogenous and endogenous mechanisms, the scenarios with social-ecological interactions also show lower levels of food security and higher levels of income inequality than scenarios with only social interactions. In other words, the absence of social-ecological interactions in the model overestimates the effect of innovation on food security and underestimates the effect on income inequality.

We demonstrate how modelers can effectively diagnose and incorporate social-ecological action situations within their models using the SE-AS framework. Most model documentation practices by SES researchers and modelers such as ODD, ODD+D (Grimm et al., 2006; Müller et al., 2013), and TRACE (Schmolke et al., 2010), highlight the model-building process with little transparency on the process of model formalization through which the modelers achieved the desired simplification (Schlüter et al., 2014). This paper serves as a demonstration of how stylized models of social-ecological phenomena can be developed as thinking tools through the application of the SE-AS framework (Schlüter et al., 2019) as a diagnostic tool. The SE-AS framework enabled us to establish the boundaries of the model, as well as visualize the social and ecological interactions within the model. Further, the focus on action-situations of key social and ecological entities supported the selection of agents, their actions, and interactions in the ABM. The framework also allowed us to make modeling decisions and assumptions more explicit and intentional toward an integrated context-dependent understanding of the intertwined nature of social-ecological innovation systems.

In the Ag-Innovation model, we included social-ecological interactions such as changes in temperature and precipitation, climate risk perception, formation of innovation beliefs and desires as well as regulatory ecological feedback on soil fertility. Model results show that these interactions and dynamics are key in influencing food security and income inequality outcomes. Climate patterns such as changes in temperature and precipitation influence both crop choices as well as crop production, where producers perceive climate risk to make crop choices, estimate crop production, and use adaptive learning from past production histories to develop innovation beliefs and desires. Once producers adopt certain innovation types, there is regulatory feedback on crop production and soil fertility. These factors together affect overall crop production, which in turn affects food security and income inequality outcomes. This insight is especially relevant for innovations oriented towards conservation, which may not offer short-term, immediate benefits, as opposed to innovations oriented towards increased production. Research has shown that the adoption of conservation practices is guided not only by economic, but also by complex socio-psychological and ecological factors such as values, beliefs, norms, and risk perception (Clearfield & Osgood, 1986; Delaroche, 2020; Knowler & Bradshaw, 2007; Greiner et al., 2009). Failure to take these fundamental social-ecological interactions into account when modelling and evaluating innovation systems could potentially lead to inaccurate assessments of the efficacy or demand of certain innovations that promote sustainable agriculture.

ii) Endogenous innovation mechanism leads to higher food security and income inequality than the exogenous innovation mechanism.

In our exploratory analysis, we compared scenarios of exogenous and endogenous mechanisms of innovation with scenarios of no innovation and explored the effect of each mechanism on food security and income inequality outcomes. We hypothesized that exogenous mechanisms would lead to higher food security and income inequality based on evidence that agricultural research organizations and extension often develop agricultural technologies that increase crop productivity (thereby leading to increased food security) and are accessible only to larger producers with enough financial resources to afford these technologies (thereby leading to increased income inequality) (Bambio et al.,2022; Ndjeunga & Bantilan, 2005; Okai, 1997). Lazarus' (2013) study based in Mali, also demonstrated that income inequality increases when agricultural improvements are targeted at larger farmers rather than smaller or poorer farmers. However, we find that while the exogenous mechanism leads to slightly better food security outcomes than a scenario where there is no innovation, the endogenous mechanism leads to higher food security as well as higher income inequality than the exogenous mechanism.

This result is surprising and contrary to our hypothesis but can be explained through differences in innovation adoption patterns and network structures within the exogenous and endogenous innovation mechanisms. Results show that the adoption rate of production-oriented innovations is much higher for the endogenous mechanism and slightly declines over time along with a synchronous increase in the adoption of conservation-oriented innovations. Adoption dynamics (including adoption patterns over time and rates of adoption) are determined both by the types of innovation desired by the producers as well as the type of innovation developed by innovators. The endogenous mechanism allows for bidirectional signaling of innovation demand and supply between producers and collective innovators as opposed to the exogenous mechanism's unidirectional signaling of innovation supply from external innovators to producers. Producer agents implement adaptive learning by assessing their past production histories to develop innovation beliefs (if innovation is needed) and innovation desires (what kind of innovation type is needed). Smaller producers who are connected to the collectives signal the most desired innovations to the collective innovators, who then develop the innovation and disseminate the innovation back to the producers. Higher proportion of smaller producers in the agricultural landscape lead to higher network strength of linked producers and collectives, making innovation signaling stronger. As a result, innovations are developed and disseminated more in line with the preferences of producers who ultimately adopt the desired innovations at a higher rate.

In the exogenous mechanism, there is no signaling of innovation desires from the producers to the external innovators, who innovate randomly. Additionally, the developed innovations are disseminated to larger farmers (early adopters) in their network, which results in lower adoption rates for two reasons: first, the innovation developed may not be the innovation the producer desires and second, the low proportion of larger producers results in a weaker network and a lower rate of adoption diffusion. Readers are cautioned, however, to not interpret these results to mean that producers inherently seek production-oriented innovations as opposed to conservation or stability-oriented innovations. The higher adoption rates of production-oriented innovations in both exogenous and endogenous mechanisms are a consequence of model parameterization where temperature and precipitation change were set to a moderate increase and decline respectively, as projected for West Africa (Giannini et al., 2017). This calibration led to a decline in crop yields, resulting in a larger proportion of producers desiring production-oriented innovations as opposed to stability or conservation-oriented innovations, which in turn led to higher adoption rates of production-oriented innovations, an increase in crop production, and ultimately, higher food security.

Model results also show that the endogenous mechanism led to higher income inequality than the scenario with no innovation. These results are also explained through the cross-scalar dynamics between producers and collectives. A larger proportion of early adopters (i.e., small and medium producers) enter a repeated cycle of capital allocation, innovation adoption, and income generation that prevents them from increasing their overall capital, thus creating “poverty traps” (Barrett & Swallow, 2006, Radosavljevic et al., 2021). On the other hand, larger farmers (i.e., late adopters), who are not connected to the collectives, do not allocate capital for innovation development, and can accumulate additional income from increased agricultural production; thereby leading to higher income inequality. A noteworthy point that needs highlighting here is that the difference in median values for food security outcomes for exogenous and endogenous mechanisms is more significant than those for income inequality. This suggests that the endogenous mechanism can be a more effective mechanism to address food security in the region despite some adverse effects of increased income inequality.

iii) Bidirectional outreach is more effective than unidirectional outreach in improving food security.
Results from the sensitivity analysis suggest that food security would improve with higher network radius and density in both the exogenous and endogenous mechanisms. Food security outcomes were not sensitive to capital allocation rate and foreign aid amount. In other words, food security outcomes would improve through higher outreach of innovation knowledge and information between producers and innovators (through wider and denser networks). On the other hand, income inequality rises with an increase in capital allocation rate and declines with an increase in innovator density and network radius. These results are neither new nor surprising. However, they emphasize how innovation agents (producers and innovators) influence food security and income inequality outcomes through the configuration and organization of their roles within innovation processes.

Characteristics, such as network radius and density, but also composition (who is in and out) between the interactions of innovators and producers determine not only how innovation knowledge is created and shared across scales, but also the signaling of innovation needs and desires. Unidirectional outreach from innovators to producers, as shown in the exogenous mechanism, is likely to be less effective than bidirectional feedback in knowledge and resources as shown in the endogenous mechanism. There is a potential for both mechanisms to operate within the innovation system through a collaborative extension service system that leverages the strengths of collective action among sets of heterogenous producers and innovators.

According to Wigboldus et al. (2016), innovation development that adheres to the justification of copying inventions that were successful in one area to another does not adequately consider complex social, ecological, and institutional realities. These innovations often are unable to scale up and may even produce undesirable effects. Our insight demonstrates the need for the development of innovations that are aligned with the ecological realities of the agricultural landscape as well as the needs and desires of farmers. Our study demonstrates how the interaction between innovators and producers plays an important role in knowledge and information transfer at all stages of innovation from innovation development, dissemination, adoption, and diffusion. As we also demonstrate, these interactions also play a large role in the success of collective innovation by facilitating knowledge creation and transfer, resource mobilization, and cooperation (Berthet & Hickey, 2018).

6. Limitations

According to Schlüter et al. (2019), models are simplified representations of reality in which the process of simplification is guided by the knowledge and assumptions of those involved in the model development process. Model results should always be interpreted considering these assumptions and the underlying system conceptualization. Our model juxtaposes two mechanisms against each other, whereas, in reality, both mechanisms can and certainly often do operate alongside each other and complement each other. This is a limitation of our model. Future investigations could consider expanding the model to examine different combinations of the mechanisms and how they interact. Additionally, we make a strong assumption in the model that in the exogenous mechanism, early adopters are larger farmers who are linked directly to external innovators while in the endogenous mechanism, early adopters are smaller farmers linked to collectives. This assumption is based on empirical evidence in the case study. However, this assumption can be relaxed to include a mix of farmer types in the networks in extensions of this model. Lastly, the model assumes that innovators develop and disseminate only one type of innovation at each time step. In reality, innovators can develop different types of innovations at the same time and offer a repertoire of innovation types that the producers can select from, but to keep the adoption dynamics simple, we maintained this assumption in the model.

7. Conclusion

We developed an empirically driven, stylized agent-based model through an iterative process of combining theory with empirical data. Our social-ecological modeling approach facilitates a deeper understanding of not only the different social-ecological dimensions of agricultural innovation but also the distinct cross-scalar mechanisms within innovation systems. Our results make a strong case for the incorporation of social-ecological interactions within the assessment and modeling of innovations in agricultural systems. Overall, results from the exploratory analysis show that food security and income inequality patterns arise due to the characteristics and configuration of innovator-producer networks and their modes of operations, goals, and actions as well as the decisions of the actors embedded within the innovation system. Contextualized knowledge of agricultural social-ecological interactions plays an important role in the success of agricultural innovations. Hence, innovation needs to be aligned with the beliefs, desires, and ecological realities of the place where innovation interventions are sought. Overall, our results highlight the need for embedding contextualized knowledge of agricultural social-ecological interactions. By viewing innovation as an adaptive process that includes both social and ecological dynamics, we obtain a complete and more nuanced picture of the dynamics within innovation processes.

Acknowledgements

The research leading to these results received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (grant agreement No 682472 – MUSES).

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