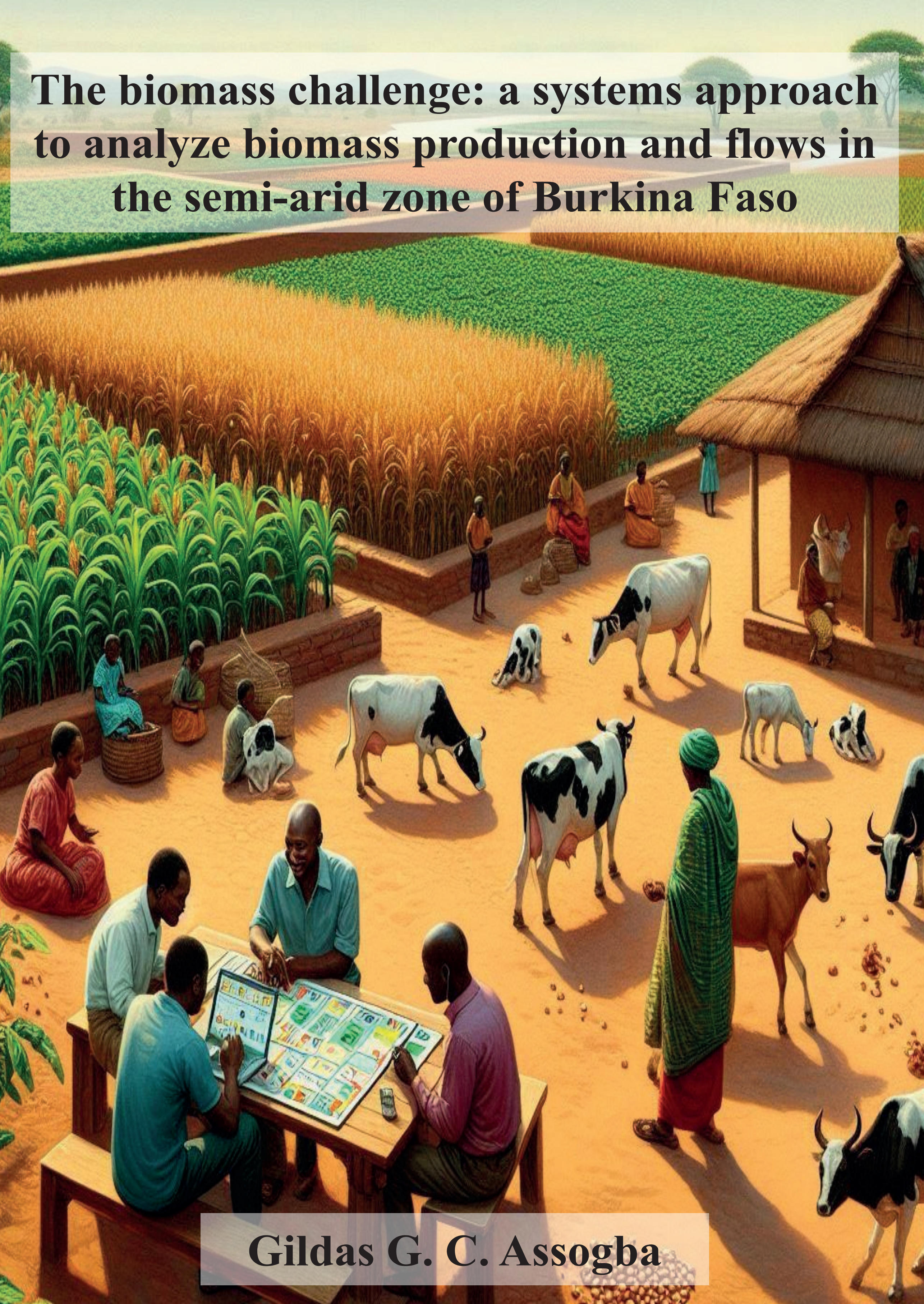
The biomass challenge: a systems approach to analyze biomass production and flows in the semi-arid zone of Burkina Faso



Gildas G. C. Assogba

Propositions

1. Improving crop-livestock integration through biophysical interventions is insufficient to improve food security for smallholder farmers in West-Africa (this thesis).
2. Combining model exploration with farmers' perceptions of their farming system offers new horizons for the co-design of agricultural innovations (this thesis).
3. The carbon footprint of computer modelling for sustainability transitions is often overlooked[*].
4. The lack of ethical regulations on artificial intelligence in sub-Saharan Africa will reduce benefits for development.
5. The involvement of sub-Saharan African countries in North-South partnerships is often incentivized by short-term benefits received from projects rather than long-term plans for development.
6. Due to the limited financial support sandwich PhDs currently receive, they are forced to join the Dutch tradition of eating a simple cheese sandwich for lunch.

Propositions belonging to the thesis, entitled

The biomass challenge: a systems approach to analyze biomass production and flows in the semi-arid zone of Burkina Faso

Gildas G. C. ASSOGBA

Wageningen, 27 February 2024

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[*] Anthony, L. F. W., Kanding, B., & Selvan, R. (2020). Carbontracker: Tracking and predicting the carbon footprint of training deep learning models. *arXiv preprint arXiv:2007.03051*.

The biomass challenge: a systems approach to analyze biomass production and flows in the semi-arid zone of Burkina Faso

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This research was conducted under the auspices of the *C.T. de Wit* Graduate School of Production Ecology and Resource Conservation

The biomass challenge: a systems approach to analyze biomass production and flows in the semi-arid zone of Burkina Faso

Gildas G. C. Assogba

Thesis

submitted in fulfilment of the requirements for the degree of doctor
at Wageningen University
by the authority of the Rector Magnificus,
Prof. Dr A.P.J. Mol,
in the presence of the
Thesis Committee appointed by the Academic Board
to be defended in public
on Tuesday 27 February 2024
at 11 a.m. in the Omnia Auditorium.

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The biomass challenge: a systems approach to analyze biomass production and flows in the semi-arid zone of Burkina Faso,

200 pages.

PhD thesis, Wageningen University, Wageningen, the Netherlands (2024)

With references, with summary in English

DOI https://doi.org/10.18174/648619

Content

1 General introduction

1.1 General context

Sub-Saharan Africa (SSA) is lagging behind when it comes to achieving Sustainable Development Goals according to the United Nations agenda (United Nations, 2023). This is particularly true for SDG2 (Zero hunger) with SSA having the highest undernourishment prevalence in several countries. Actually, food production in SSA relies on smallholder farmers with limited livelihoods and diverse levels of food security (Giller et al., 2021). Consequently, SSA depends on massive imports of food to improve food availability to its population. For example, in 2021, food imports in SSA represented 114% of food exports while food exports was only 22% of food produced (FAOSTAT, 2023). However, even that dependency on imports does not currently guarantee food security in the region.

Burkina Faso, a low-income country in SSA is also concerned by the aforementioned characteristics. The country is among the ten poorest countries in the world (UNDP, 2023) and severe food insecurity affects an estimated 55% of the population (FAOSTAT, 2023). While agriculture is the first employer in the country involving 73% of the population (World Bank, 2023), it only contributes to 17% of the national GDP. Despite a modestly positive trend in the yields of main crops and herd size in the country (Figure 1.1a), agricultural productivity is still poor and food security has not significantly improved. In order to cope with the needs of the fast-growing population, agricultural expansion rather than intensification is taking place (Figure 1.1b). However, agricultural expansion in the country has been associated with deforestation and land degradation (Dimobe et al., 2015). Sustainable intensification of agriculture is needed to support adequate and nutritious food production in the long term.

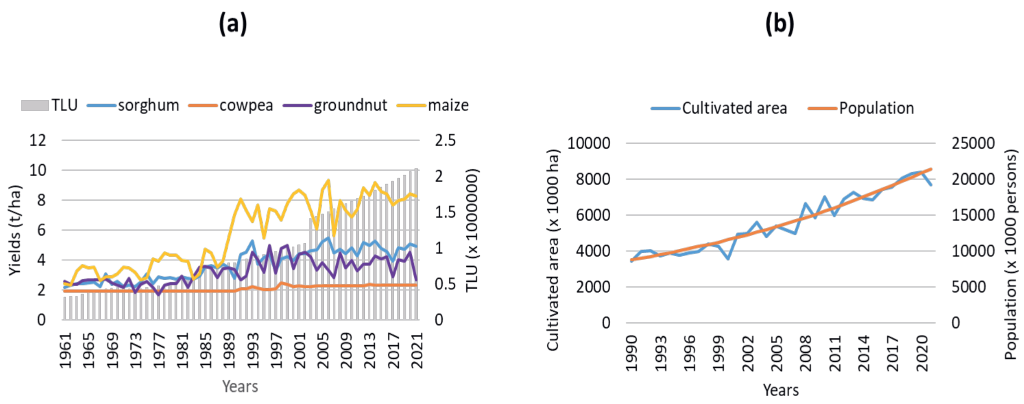


Figure 1.1: Trend in main crop yields and livestock (cattle, goats and sheep) herd size in Burkina Faso (a). Trend in cultivated area and population size (b). TLU = tropical livestock unit. Source: (FAOSTAT, 2023).

Agriculture in Burkina Faso is dominated by smallholder farmers combining crop and livestock production in mixed farming systems. Mixed farms combine crop and livestock production which offers opportunities for nutrient recycling and income diversification. Theoretically, mixed crop-livestock farms allow relatively high crop and livestock production with minimal dependence on external inputs compared to specialized crop or livestock farms (Powell et al., 2004). Crop residues can be fed to livestock, which, in return, provide manure to fertilize fields. Livestock can also be used as animal draught for ploughing and provide cash from meat and milk selling. Nevertheless mixed farms also imply dependencies between the cropping and the livestock components, and the overall performance of the farming system depends on the ability of the crop and livestock components to support each other. Crop production in mixed farming systems of Burkina Faso is characterized by large yields gaps (Figure 1.2), associated with limited nutrient inputs under the mostly rainfed conditions. Therefore, the amount of feed produced for livestock in the form of crop residues is also limited. This limited feed availability creates a trade-off between the different objectives associated with the use of crop residues, such as maintaining soil fertility (mulching) and feeding livestock (Andrieu et al., 2015; Berre et al., 2021). Consequently, livestock performance, including production and reproduction, is limited and farmers rely on grazing areas to feed their livestock (Otte and Chilonda, 2002). However, the high stocking density of livestock in grazing areas often results in their degradation (Fynn and O'connor, 2000). Moreover, the manure produced by livestock is usually not enough to compensate for nutrient loss in the cropping system (Diarisso et al., 2016). Therefore, the potential synergies and complementarities between crop and livestock production are not exploited in the current systems.

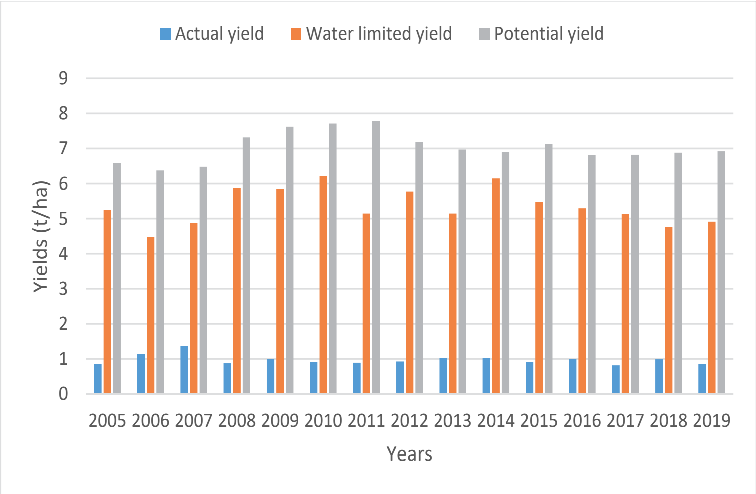


Figure 1.2: Actual, water limited, and potential yields of sorghum in Burkina Faso. Source: Global Yield Gap Atlas, 2023 https://www.yieldgap.org/

1.2 Justification of the research

Mixed farming systems in semi-arid West Africa face many challenges such as the growing population (World Bank, 2023), climate variability (Sanou et al., 2023) and declining soil fertility (Diarisso et al., 2016). There is urgent need to find suitable solutions to improve agricultural production in a sustainable way.

Several studies have been conducted in mixed farms of semi-arid Burkina Faso with a focus on a particular component of the farm and farming systems and for various purposes, such as enhancing soil fertility and crop productivity (Adams et al., 2020), reducing pest and diseases damage (Cuevas et al., 2016; Georges et al., 2008) and producing better feed for livestock (Zampaligré et al., 2022). However, farming systems are complex as they involve biophysical (e.g. soil) and social (e.g. farmers) components influencing each other. Studies in Burkina Faso that consider the complexity of whole farms through investigating interactions and feedbacks between its components are few (Diarisso et al., 2015). Studying farm systems from a holistic instead of a particular point of view offers opportunities to better account for possible synergies and trade-offs associated with interventions in the farms. However, the holistic approach alone is not sufficient to find solutions that are appealing to farmers. Farmers' perspectives and knowledge of the farming systems is also key and valuable as including farmers in participatory research can help in finding options that are relevant to them and hence have a better chance of improving farming system's overall performances (Dissa, 2023; Falconnier, 2016).

Furthermore, the integration level at which research is taking place also matters (Figure 1.3). To understand the potential performance or effects of an intervention, it is necessary to look at least one level up and one level down. For example, at field level fertilization may lead to improved yields, but at farm level this may not be feasible as smallholder farmers often cannot afford fertilizers because of their limited income. Hence, just considering field-level effects of an intervention leads to ignoring important constraints (e.g. financial capital) for farmers to adopt the intervention. Existing studies mostly focused on field and sometimes farm level with far less attention to the village level. However, farm performance depends not only on individual management but also on the interactions between farms (Andrieu et al., 2015). These interactions can be either direct (e.g. exchange of seeds) or indirect (free grazing on crop residues). In addition, the spatial organization of the village also has an impact on nutrient recycling (Grillot et al., 2018b). For example, the availability of feed in grazing land and cultivated fields determines livestock mobility across and out of the village (Berre et al., 2021). In addition, the distance between fields and farmers' settlement can also impact the spatial distribution of nutrients and soil fertility (Grillot et al., 2018a). In fact, depending on the spatial configuration of the village (e.g. ring management), fields that are close to settlements and thus require less labor and transport efforts receive more nutrients (manure, households waste and fertilizer) than distant fields. Additionally, rangelands and fallows that are used as grazing land also impact the spatial distribution of nutrients and soil fertility.

Analyzing farming systems also require to consider multiple dimensions involved, which include at least productivity, economic, social and environmental considerations. In fact, these dimensions are key in evaluating the sustainability of the farming system itself as well as options investigated to improve the system (Descheemaeker et al., 2018). In order to improve crop-livestock production, many studies focused on the productivity and/or environmental performances (Adams et al., 2016; Bado et al., 2012). Nevertheless, integrating the multiple dimensions in farming systems allows to account for possible trade-offs between sustainability dimensions. For example, when investigating plot level intensification options in maize-based systems in Malawi, Snapp et al. (2018) demonstrated trade-offs between productivity, profitability and soil fertility. They also identified potential accrual competition for crop residues between crop and livestock production at farm scale. In addition to researchers' sustainability criteria, farmers' perceptions of researched options are also key as farmers often value different criteria than researchers when evaluating an option (Falconnier et al., 2017). These criteria can be related to labor availability, market opportunities as well as productivity and financial risks associated with investigated options.

Hence, because of the complexity of the farming system described above, finding adequate solutions to increase crop-livestock integration and production is a challenge. Therefore, this thesis comprises a multiple level analysis of the farming system to account for social, spatial and ecological dimensions, and interactions and feedbacks in the system. Interactions and feedbacks between components of the farming system are simultaneously analyzed at field, farm and village level. The key levers and solutions to improve crop-livestock integration and production are explored in a participatory way. The involvement of farmers in the research aimed at co-learning with them through knowledge sharing. Farmers' perceptions were also essential in assessing the relevance of researched options targeting increased crop-livestock production.

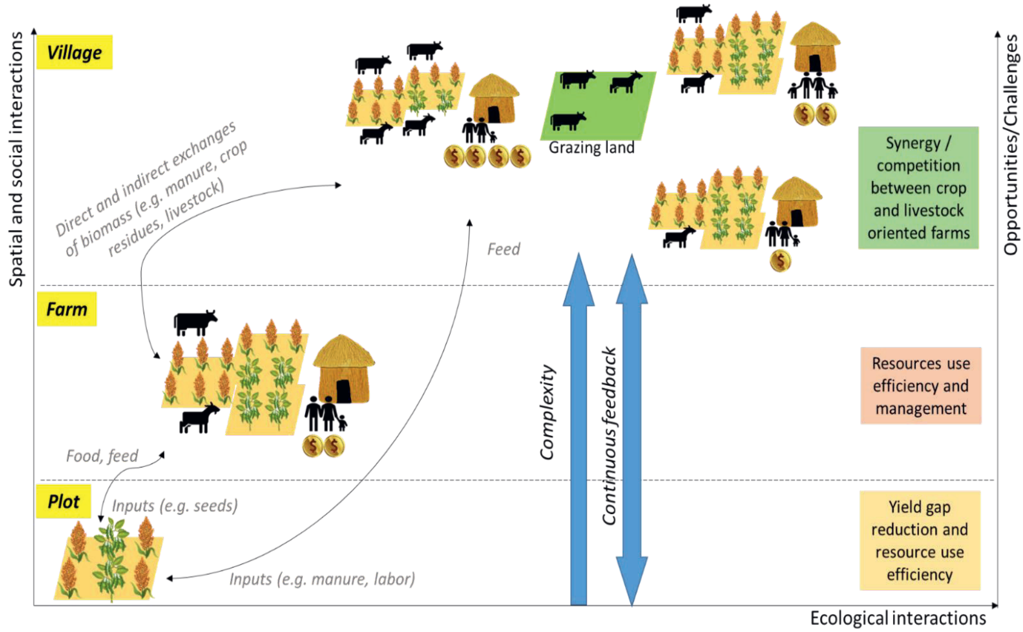


Figure 1.3: Schematic representation of multi-level interconnections and multiple dimensions included in the farming system.

1.3 Study area

The research took place in the semi-arid zone of Burkina Faso. The country is divided into three major agro-ecological zones along a south-north gradient (Figure 1.4). The Sudanian zone in the southern part of the country has an annual rainfall ranging from 800 mm to 1100 mm. The Sudano-Sahelian (semi-arid) zone located in the central part of the country has an annual rainfall ranging from 500 mm to 800 mm. The semi-arid zone is a transition zone between the Sudanian zone and the Sahel. The Sahelian zone is located in the northern part of the country and is the driest of all with annual rainfall less than 500 mm.

Agriculture in the semi-arid zone is dominated by crop-livestock and agro-pastoralists farms. The first include sedentary farmers combining crop production with relatively small herd size whereas the latter include semi-nomadic farmers with large herd size who grow crops during the rainy season and move southward in search for forage during the dry season. Contrary to the Sudanian zone, cash crop (e.g. cotton) production is scarce and crop production is oriented on staple food production with sorghum being the dominant crop. Biomass (grains, crop residues, livestock and manure) production in semi-arid Burkina Faso is low and unstable due to insufficient nutrient inputs and rainfall variability (Diarisso et al., 2016; Sanou et al., 2023). Food insecurity in the semi-arid zone is significant (Fraval et al., 2020) and feed scarcity aggravates the trade-off between mulching for soil fertility improvement and feeding the livestock (Rodriguez et al., 2017).

This study is part of the 3F (Feed the soil, Feed the cow to Feed the people) and SESAM (Scenario Evaluation for Sustainable Agro-forestry Management) projects. The projects targeted two villages in semi-arid Burkina Faso: Yilou and Tansin. 3F built on previous research projects implemented in the same location. Examples of previous research projects are ORACLE, RAMSES II and ABACO which researched respectively crop diversification with legumes, intensification of agroforestry practices and conservation agriculture.

Acrisols and Lixisols are the main soil types encountered in Yilou and Tansin (https://soilgrids.org/ accessed on 15/11/2023). The two villages contrast by their size, water access and market opportunities. Yilou covers 35 km^2 whereas Tansin is smaller with 4 km^2. There is a temporary river in Yilou which allows some farmers to produce vegetables at the end of the rainy season. The river is also a source of water for livestock in the village. Contrary to Tansin which is more isolated (13 km from the market), Yilou is crossed by the national road which offers trading opportunities with surrounding cities such as Kongoussi. The study area is part of the Mossi plateau, the main ethnic group in Burkina Faso. The most spoken language in the study area is Mooré.

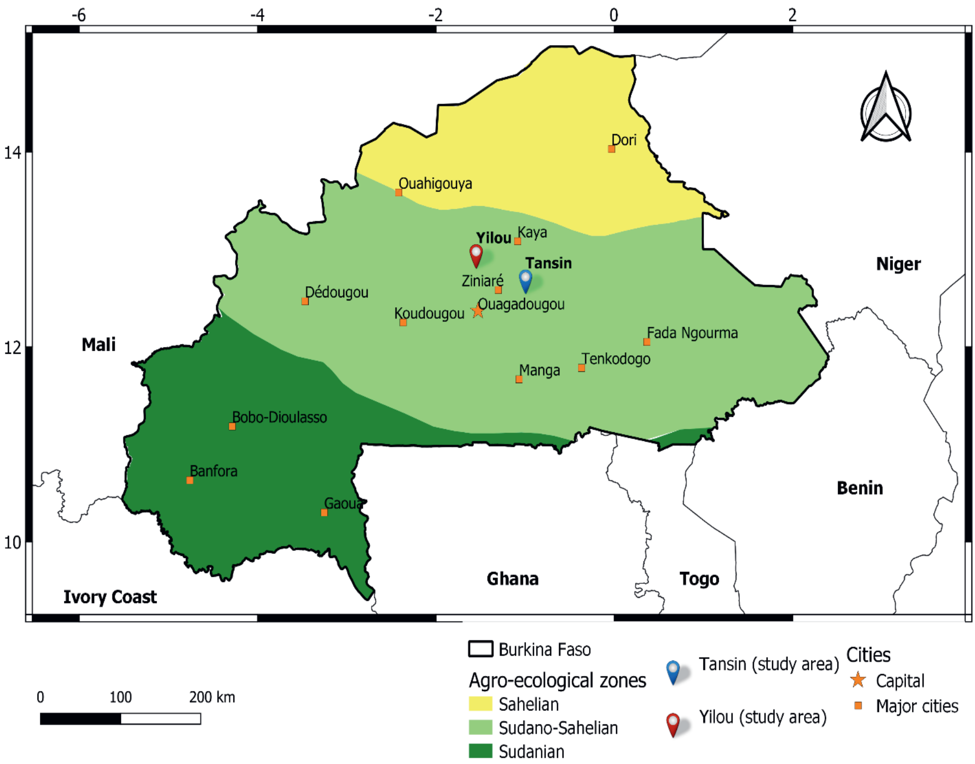


Figure 1.4: Study area location in agro-ecological zones of Burkina Faso.

1.4 Research question and objectives

With an overall goal to contribute to improved food security and livelihoods of smallholder farmers, the overarching question of this thesis is how systems research can reveal levers and interventions to improve crop-livestock integration and production in West-Africa. To answer this question, the thesis is articulated around four objectives:

1- To identify key levers to improve biomass management in semi-arid Burkina Faso (chapter 2).

2- To assess the extent to which current farm management is able to sustain crop and livestock production and fulfil household food requirements (chapter 3).

3- To better understand farmers' decision-making and explore mixed farm systems for stronger crop-livestock integration and production (chapter 4).

4- To explore the impact of legume diversification on biomass production and flows, households' food self-sufficiency and income, as well as nutrient balances and use efficiency at farm and village level in semi-arid Burkina Faso (chapter 5).

1.5 The methodological approach

This thesis is based on a participatory and interdisciplinary research approach that is known as the DEED (Describe, Explain, Explore and Design) approach (Descheemaeker et al., 2019; Giller et al., 2011). Farmers were involved in all phases of the research. They provided data for the farming system description and actively helped in collecting data used to explain the current state of the farming system. Farmers also shared their perceptions of alternative options targeting increased crop-livestock production during participatory explorations. Farmers' involvement in the research offers opportunities to bridge the gap between farmers' and researchers' perceptions of the farming system. In addition, the overall approach of this thesis combines knowledge from relevant fields of study (agronomy, livestock science, modelling, geographic information system and social learning) to better account for multiple dimensions and levels (Figure 1.3).

Semi-arid Burkina Faso is a data scarce environment. Therefore, extensive data collection was needed in order to describe, explain and explore the farming system. To describe and explain the current state of the farming system, an individual household survey was set up combined with focus group discussions to better account for farmers' perceptions of the farming system. A statistical farm typology (Alvarez et al., 2014) backed up by farmers' typology was developed and the related biomass production and management was analyzed. In addition, the data from survey and focus group were combined in Fuzzy Cognitive Maps (FCMs) (Kosko, 1986) to explore key levers to improve biomass production and management per farm type. The advantage of a FCM is that it does not require extensive amount of data on the farming system and can combine both quantitative and qualitative variables. Furthermore, a farm monitoring tool was developed together with farmers. This tool helped in detailed data collection on all components of the farm system to better explain the current state of the farming system. Farmers were also involved in the detailed farm monitoring.

The farming system was further explored with a serious game and an agent-based model (ABM). Both the serious game and the ABM built on the results of the statistical analysis of data from households' survey, focus group discussion and farm monitoring. As there was no existing serious game to explore African mixed farming systems, a new game was developed with farmers and local researchers in an iterative process in which the game was continuously updated based on farmers' and researchers' feedbacks. The design of the game started with the ARDI (Actors Resources Dynamic and Interactions) approach (Etienne et al., 2011) allowing to account for the dynamics of social and ecological relations between components of the farming system. The results from the ARDI were combined with biophysical information collected on the farming system to design the game. Serious games offer opportunities to foster communication between farmers and researchers (van Noordwijk et al., 2020). In addition, an exploration of the range of possible outcomes of the game was applied (Sari et al., 2024). The exploration has the advantage of revealing undesirable game outcomes and can lead to the adjustments of the game mechanic. The game exploration looked for trade-offs and/or synergies between the game outputs as well as optimal solutions and how to reach them. The outcomes and strategies of game participants (farmers) were compared to the ones leading to the optimal solutions. Finally, data collected through the survey, focus group discussion, farm monitoring and with the serious game were included in the development of an agent-based model. Agent-based modelling has the advantage to be a bottom up approach, building from individual farms to let patterns emerge at village level. The modelling approach also accounts for spatial and social interactions as well as feedbacks in farming systems. The agent based model was then used to analyze biomass production and flows at multiple levels in the farming system. Beyond the development of the ABM, further exploration was applied to test the robustness of the model and look for alternative farm management possibly leading to improved crop-livestock production. The robustness of the model was assessed with a sensitivity analysis (Borgonovo et al., 2022). Moreover, alternative farm managements and associated trade-off and/or synergies across levels were investigated based on Pattern Space Exploration (PSE) (Chérel et al., 2015).

1.6 Thesis outline

This thesis is made up of four chapters in addition to the general introduction and discussion. The four chapters are interrelated and represent the core of the thesis (Figure 1.5). These chapters are centered on the four specific objectives of the thesis.

Chapter 2 describes farm diversity and related biomass management as well as key levers to improve biomass production. This chapter forms the basis of chapters 3, 4 and 5. The diversity of farms described in chapter 2 was used as basis for detailed farm monitoring in chapter 3. Volunteer farmers representing the diversity of farms identified in chapter 2 were involved in weekly biomass and nutrient flow measurements at field and farm level. Therefore, chapter 3 provides detailed information on each component (soil, crops, livestock and households) of the farm system. Information collected in chapter 3 was used to explain the current state of the farming system. This information was later used to explore the farming system. Exploration of the farming system was done in chapters 4 and 5 with the ambition of finding relevant and tailored options to increase crop-livestock integration and production.

Results of chapters 2 and 3 were fed into chapter 4 to perform a participatory exploration of promising options to increase crop-livestock production. The participatory exploration was done using a serious game co-designed with farmers and local researchers. The game was played by farmers and their decision-making in the game as well as potential differences with real-life were analyzed. Finally, the results from chapters 2, 3 and 4 were combined in chapter 5 for a multiple level (plot, farm and village) analysis of the farming systems and quantifying the impacts of the options at farm and village level. An agent-based model was developed to achieve the multiple level analysis of the farming system in chapter 5.

Chapter 6 is the general discussion of the thesis. The methodological approach used in the thesis as well as results are discussed. Chapter 6 also includes strengths and limits of the present thesis as well as perspectives.

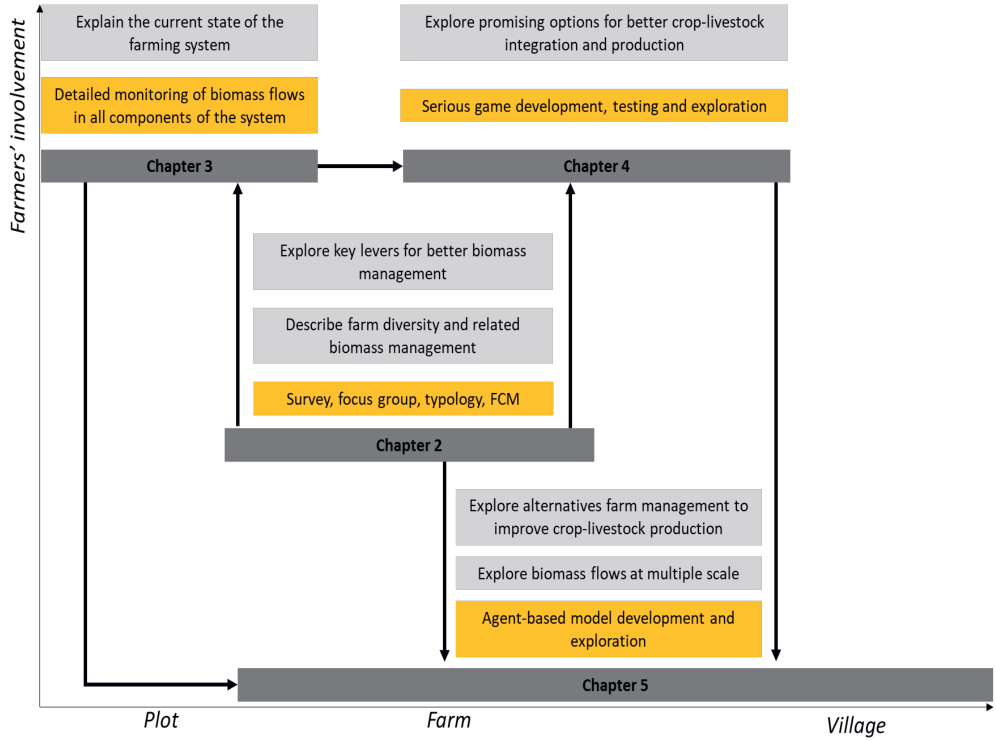


Figure 1.5: Schematic representation of the four chapters representing the core of the thesis and their relations. Farmers' involvement relates to time investment and/or data provision during the research. Dark gray boxes refer to chapters, light gray boxes refer to key achievements and golden boxes refer to main methods applied in a chapter. FCM = Fuzzy Cognitive Map.

2 Managing biomass in semi-arid Burkina Faso: Strategies and levers for better crop and livestock production in contrasted farm systems†

† This chapter was published as:
Assogba, G. G., Adam, M., Berre, D., & Descheemaeker, K. (2022). Managing biomass in semi-arid Burkina Faso: Strategies and levers for better crop and livestock production in contrasted farm systems. Agricultural Systems, 201, 103458.

Abstract

CONTEXT

The semi-arid zone of Burkina Faso is characterized by strong climate variability and declining soil fertility associated with low biomass production.

OBJECTIVE

The main objective of this study was to identify key levers to improve biomass management in semi-arid Burkina Faso for diverse farm types.

METHODS

Farm diversity was captured with a statistical typology complemented by a participatory typology established with local farmers. Biomass management was described for the different farm types based on survey information obtained from 228 households across two villages. Fuzzy Cognitive Mapping (FCM) was conducted to represent biomass production strategies of each farm type. After a sensitivity analysis which revealed model robustness, scenario analysis was performed with the FCMs to explore farm type-specific options for alleviating biomass scarcity. Two contrasting scenarios were built based on observations and insights from the survey and focus group discussions with farmers and included (1) deliberate exchange of crop residue with manure, and (2) a subsidies policy allowing a reduction in prices of 30% for farm inputs coupled with increased off-farm revenue for the subsistence-oriented farms.

RESULTS AND CONCLUSIONS

The statistical typology identified four farm types, distinguishing between subsistence or market-oriented farms and crop or livestock-oriented production. The participatory typology partly confirmed these four main types, even though other criteria of distinction were given by farmers. Different farm types used contrasted strategies in biomass production and management which were mainly driven by the total cultivated area and the herd size. The farm type with the largest herd and smallest cultivated land was the only one to rely on grain inflow from outside the farm to meet its household food requirement. The inflow of crop residue was also largest for this farm type. In contrast, crop residue outflow was mainly observed for the subsistence-oriented crop farm type, which had the smallest fodder needs. The scenario analysis using FCM suggested that biomass exchange had a negligible effect on farm performance but that the subsidy and income diversification scenario positively impacted crop and livestock production, especially for the subsistence-oriented types.

SIGNIFICANCE

Our study pointed out that FCM is a useful tool to not only describe system dynamics but also to reveal levers for improvement through sensitivity and scenario analysis. These levers included income diversification (for subsistence farms especially), improved production and storage of forage (for large herd owners), and investment into equipment and better access to markets (for market-oriented farms).

Keywords: Farm diversity, Modelling, Policy, Sub-Saharan Africa.

2.1 Introduction

Agriculture in sub-Saharan Africa (SSA) faces major challenges, related to climate variability, decline of soil fertility, low level of equipment and organization of farmers in rural areas (Sheahan and Barrett, 2017; Tully et al., 2015). Cropping systems in SSA are characterized by large yields gaps (van Ittersum et al., 2016) caused by inadequate fertilization and irrigation (Awio et al., 2021; Diarisso et al., 2016). In addition, risks related to rainfall variability, pests and diseases often cause crop failure leading to increased food insecurity and even famine (Barbier et al., 2009; Fraval et al., 2020). Considering the low-level of resource-endowment of smallholder farmers and the quasi-absence of credit opportunities, adequate investment in farming is extremely difficult and farmer can be locked in the so-called “poverty trap” (Tittonell and Giller, 2013).

Agriculture in the semi-arid region of Burkina Faso is not an exception to the above-mentioned characteristics. The region is dominated by mixed farms combining crop and livestock production. In such farming systems, better crop-livestock integration has been proposed as a solution to improve farm performances and resilience (Duncan et al., 2013; Tarawali et al., 2011). Indeed, the combination of crops and livestock is considered as a means of diversification, improvement of nutrient recycling and resource use efficiency (Baudron et al., 2014; Tui et al., 2015). This can be achieved through improved feed quantity and quality, good land management practices such as cereal-legume intercropping or rotations, improved manure management and livestock husbandry (Castellanos-Navarrete et al., 2015; Franke et al., 2018; Hassen et al., 2017).

However, adoption of these practices has been limited (Giller et al., 2009) mainly because of socio-economic constraints leading to low nutrient inputs and labor availability, which in turn result in poor grain and biomass yields (Franke et al., 2019). In systems characterized by a low level of intensification, biomass scarcity limits better integration between crops and livestock. Indeed, the amount of crop residues is mostly insufficient to feed both the livestock and maintain soil fertility through mulch (Baudron et al., 2014). Farmers usually prioritize their livestock as it contributes to labor, capital, income and manure production, which also contributes to soil fertility (Diarisso et al., 2016). Moreover, because of the scarcity of crop residues and lack of grass in the grazing land to feed the livestock, farmers often entrust part of their livestock to herders during the dry season. These herders generally move southward to sub-humid areas where biomass is more abundant (Zannou et al., 2021). This spatial dynamic negatively affects the amount of manure that would otherwise be available for farmers (Berre et al., 2021), and climate change is expected to alter migratory patterns and the associate biomass flows because of its negative impacts on fodder and water availability for livestock (Descheemaeker et al., 2016; Rojas-Downing et al., 2017)

Finding appropriate levers for improving farm performance in SSA can be challenging because of the low resource endowment of farmers. In addition, farm management is heterogeneous, because farming systems involve diverse and interacting households that manage their resources differently. Considering farm diversity is therefore important to provide tailored solutions to farmers (Descheemaeker et al., 2019). Often, statistical typologies are used to provide an overview of diversity at a certain point in time. Whereas typology methods can vary, ideally they are objective-driven and depend on the research hypothesis (Alvarez et al., 2018). However, a major limit of this approach is its dependence on (i) the particular hypothesis used and (ii) data selection and data quality (Alvarez et al., 2018; Berre et al., 2019; Lacoste et al., 2018). To partly address this limit, the statistical typology can be confirmed with a participatory one to verify whether it reflects the diversity that actually exists (Kuivanen et al., 2016; Lacoste et al., 2018). In addition, including farmers in the process of understanding the complexity of their farming systems, supports the design of locally-suited solutions to improve crop and livestock production that have a higher adoption potential (Sempore et al., 2016).

The complexity of farming systems partly induced by farm diversity can be unraveled using systems approaches which allow the understanding of farming system functioning (Descheemaeker et al., 2018; Tittonell et al., 2010; Van Wijk et al., 2009). Most often experimental trials, farm monitoring and mechanistic models are used to assess and explore farming systems (Descheemaeker et al., 2018; Falconnier et al., 2020). While these approaches are potentially accurate and provide quantitative outputs allowing in-depth analysis, they also require an extensive amount of data to draw conclusions on the performances of the farming systems. In the absence of such data and in order to obtain a global understanding of farming systems in semi-arid Burkina Faso, we used Fuzzy Cognitive Mapping to understand and explore solutions for biomass production and management considering the multiple interactions within a farm. A Fuzzy Cognitive Map (FCM) is a graph-based representation of a system including interactions and feedbacks between components of the systems and can integrate both quantitative and qualitative information (e.g. yield and food security) (Kosko, 1986). Fuzzy Cognitive Mapping is a relatively easy way to represent complexity, as such allowing to capture differences in farm types without the need to develop a full mechanistic model. In the particular case of farm systems, FCMs can be used to identify components (and combination of them) that represent levers for improvement that may not be revealed by considering components separately. Fuzzy Cognitive Mapping has successfully been applied to represent and analyze socio-ecological systems (Aravindakshan et al., 2021; Kok, 2009; Murungweni et al., 2011). Farming system functioning has also been studied with FCMs (Aravindakshan et al., 2021; Murungweni et al., 2011), but to the best of our knowledge, this is the first time Fuzzy Cognitive Mapping is applied to explore biomass management strategies in farming systems. Indeed, we used Fuzzy Cognitive Mapping to explore levers for better biomass production and management in semi-arid Burkina Faso. Knowing that biomass production and management strategies vary between farms (Diarisso et al., 2015), our modelling exercise focused on farm types existing in the study area.

The overall objective of this study was to identify key levers to improve biomass management in semi-arid Burkina Faso. More specifically, the four specific objectives of the study were: (1) understanding farm diversity, (2) describing biomass production and management strategies in relation to farm diversity, (3) exploring biomass management strategies through Fuzzy Cognitive Mapping, and (4) identifying levers for improved biomass production and management.

2.2 Materials and methods

Our methodology included several steps. First, the farming system diversity was described using a statistical typology complemented by a participatory typology. Results of these typologies were discussed with farmers. Second, biomass production and management strategies were analyzed for the diverse farms identifies in step 1. The information from the first and second steps was used to design a FCM for each farm type. Then a sensitivity analysis was performed on each FCM to test its robustness, and to identify levers for improved biomass production per farm type. Finally, the FCMs were used to explore scenarios aiming at increasing crop and livestock production.

2.2.1 Study area

The study was conducted in two villages: Yilou and Tansin, located in the 'Centre-Nord' region of Burkina Faso. Yilou is located at 13.02°N; 1.55°W in the province of Bam along a national road with better access to market, whereas Tansin is more isolated and located at 12.76°N; 0.99°W in the province of Sanmatenga. The region is characterized by a Sudano-Sahelian climate with one rainy season ranging from July to October. The annual rainfall is variable and ranges from 452 to 1157 mm (1964-2019 period) with an average value of 676 mm. The average monthly maximum temperature is 39°C in April whereas the minimum temperature is 17°C in January. Agriculture is the main activity in the region with sorghum, millet, cowpea, peanut and sesame being the most cultivated crops. Most farms integrate crop cultivation and livestock keeping (Diarisso et al., 2016).

2.2.2 Household survey

A household survey was carried out in Yilou and Tansin to establish a statistically-based farm typology, and to assess biomass management strategies according to farm type. The Rural Household Multi-Indicator Survey (RHoMIS, (Hammond et al., 2017)) was used as a tool to gather farm-level information, including households' composition, crop and livestock production, nutritional diversity, food security and off-farm activities. The standard version of RHoMIS was modified to also include the following aspects of biomass management: crop residue management, livestock inflow (bought, received from other farms) and outflow (sold or given away), grain and manure management, and biomass (crop, livestock and other agricultural products) exchange between households. Biomass production and management were estimated by farmers during the survey, implying that the accuracy of these estimations can be low (Fraval et al., 2019). However, rather than an accurate assessment, the aim of this survey was to obtain a broad understanding of biomass production and management per farm type. Quantities in the survey were reported by farmers using local units, which we converted into kg by weighing them directly three times and calculating the average values. In total, 228 households (farms) were surveyed in both villages. In the study context, each household managed one farm, so the words "household" and "farm" were interchangeable. Due to the small size of Tansin, we were able to survey every households (65 households) in the village whereas in Yilou, 163 households out of 582 (28%) were investigated across all village districts. In each district of Yilou, households approached and willing to participate in the survey were investigated. We investigated as many households as possible in the limits of the available budget. The data collected referred to the period ranging from July 2018 to June 2019, covering an entire year starting with the 2018 rainy season. Five trained enumerators conducted the survey using the Open Data Kit (ODK) platform for data collection.

2.2.3 Focus group discussions

Two focus group sessions were organized in each of the two villages with the sole aim to establish a farm typology according to farmers' criteria. During each session, an interview guide was used to collect data on the farmer-based typology. Of the households involved in the survey in Tansin and Yilou, 15% and 20%, respectively, also participated to the focus group sessions. Each focus group session involved 20 farmers (men or women only) divided into four sub-groups of five people to avoid excessive power influence on respondents' answers. In each sub-group, participants were asked to classify farms in the village first according to their wealth, followed by their crop and livestock production goals (subsistence, selling, both). Once they did so, they were asked to provide an exhaustive list of criteria (e.g. number of cattle owned, number of tricycle in the household) for each farm type they identified. Then, for each criterion mentioned, participants provided thresholds discriminating the identified farm types. The average value of thresholds across the villages given for each criteria was calculated to obtain a robust estimate across the groups.

2.2.4 Farm typology and related biomass management

Two different farm typologies were established. First, a statistical typology was based on variables reflecting resource endowment and production goals (Table 2.1) following the procedures described in Alvarez et al. (2018) and used the RHoMIS survey data. This statistical typology was obtained using a Hierarchical Clustering based on Principal Components Analysis (PCA) using the data from both villages. The second typology was a rule-based classification of the farms involved in the survey according to the criteria and thresholds (average values) provided by farmers during the focus group sessions (Table 2.1). Indeed, for all farm types identified by farmers, the criteria and average values of thresholds were combined into a decision tree which was used to classify farms involved in the survey. After establishment, the two typologies were discussed in subsequent plenary sessions with farmers for validation (one session per village). No change were made to the two typologies after discussion in the plenary sessions. Following Kuivanen et al. (2016), we qualitatively compared the statistical and participatory typologies (the types and distinguishing criteria) to explore differences in the categorization of farmers' diversity and to assess to what extent the statistical typology fitted farmers' perception of farming system diversity.

Table 2.1: Variables used for statistical and participatory typologies

	Variable name	Description	Units
Statistical typology	hhpop	Number of persons in the household (adult and youngs)	-
	totalcultivarea	Total cultivated area	ha
	landrentinratio	Proportion of the total cultivated land that is rent by the household	%
	tlu	Tropical Livestock Unit	TLU
	smallrumratio	Proportion of small ruminants in the herd	%
	totincome	Annual total income of the household	FCFA*
	cropinprop_onf	Contribution of crops to the household on-farm income	%
	livinprop_onf	Contribution of livestock to the household on-farm income	%
	offfarmprop	Contribution of off-farm activities to the household total income (proportion)	%
Participatory typology	Cattle	Number of cattle in the household	-
	Total cultivated area	Total cultivated area	Ha
	Tricycle	Number of tricycles in the household	-
	Motorbike	Number of motorbikes in the household	-
	Cart	Number of carts in the household	-
	Off-farm income	Contribution of off-farm activities to the household total income (proportion)	%

* 1 EUR=655 FCFA; TLU=Tropical Livestock Unit

The biomass management strategies were analyzed based on the survey data and using the statistical farm types as the unit of analysis. In the present study, the term biomass encompasses the following elements: crop residue and grain, livestock, manure, bran and concentrate fed to livestock. Biomass inflow and outflow were considered. Biomass inflow referred to biomass harvested, bought and received from other farms, whereas outflow involved biomass sold and given away to other farms. The proportions of grain and livestock sold relative to grain produced and herd size respectively were calculated as indicators of outflow intensity. In addition, direct biomass exchange between households was assessed. The non-parametric Kruskal-Wallis multiple comparisons test was used to test differences between farm types.

2.2.5 Fuzzy cognitive mapping

Fuzzy cognitive mapping is a semi-quantitative method that helps to consider multiple interactions and feedbacks in complex systems (Kok, 2009; Murungweni et al., 2011). Fuzzy Cognitive Maps (FCMs) were developed to represent the findings on biomass production and management in the different statistical farm types. The FCMs were then used as a tool to explore possible levers to improve biomass production and management at farm level.

The FCMs were made up of nodes, further referred to as concepts. The concepts were inter-connected by links (directed edges) which represent a positive or negative impact of one concept on another. The magnitude of the relation between two concepts is given by the weight of the directed edge. These weight values can vary from -1 to 0 for negative impacts and from 0 to 1 for positive impacts, with 0 meaning no impact. The stronger the relation between two concepts, the higher the absolute value of the weight affected to the directed edge. FCMs of all farm types had the same concepts and links, but differed in their values of the weights associated to the links. The choice of weights values for each farm type was a subjective process based on insights from the analysis of the survey data (2.3.1 and 2.3.2). This subjectivity is recognized as a drawback of the fuzzy cognitive mapping method (Kok, 2009).

Five main categories of concepts were included in the FCMs to represent biomass production and management: crop grain, crop residue, concentrate feed, livestock and manure (Figure 2.1, purple box). For each of these concepts, the production, inflow and outflow were considered (2.2.4). For example, crop grain is represented by three concepts: grain harvested, grain sold and grain bought. In addition, the FCMs also included resource concepts, such as on-farm and off-farm income (Figure 2.1, green box), and production factor concepts, such as fertilizer, field productivity and machinery-labor (Figure 2.1, red box). The concept field productivity encompassed soil fertility and weed management whereas machinery-labor represented labor availability in the household, including the work force from humans, animals and machines. Finally, food security, representing the ability of the household to meet its food requirement throughout the year, and risks, encompassing the impact from hazards related to climate variability, pests and diseases, were included in the FCMs (not shown in the simplified FCM of Figure 2.1 but in Figure 2.6).

Three key assumptions in the development of the FCM, included that only cattle produced manure, subsistence farms did not owned cattle, and there was no manure to be collected from pasture land.

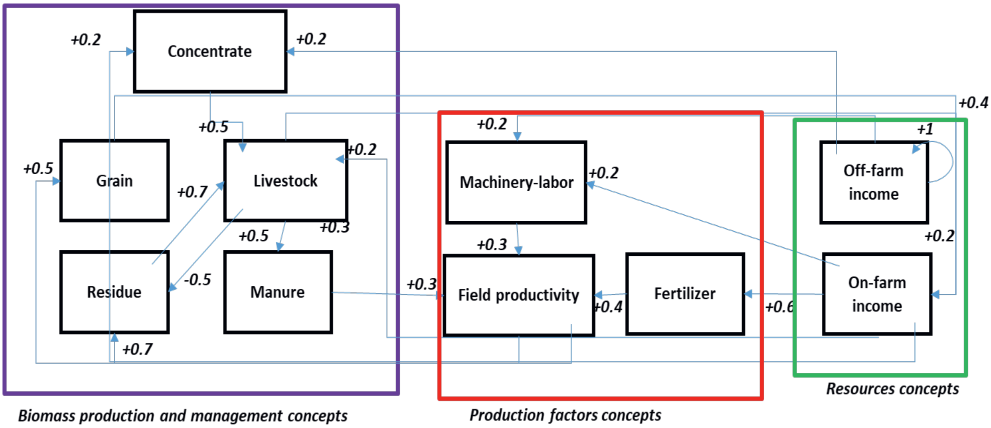


Figure 2.1: Representation of a simplified FCM (Fuzzy Cognitive Map) that forms the basis for the farm type-specific FCMs. Black squares are the concepts, the arrows represent the directed edges (links), and values on the directed edges are the weights associated to the relation between two concepts. In this example, Off-farm income is a driver of the system i.e. an external concept with no incoming arrow from other concepts but impacting the system dynamic. Auto-arrow on Off-farm concept represents self-reinforcement of this concept. All weights in the figure are fictive and used as an example. Not all the concepts present in the farm type-specific FCMs are drawn for better visualization.

2.2.5.1 FCM calibration and Sensitivity analysis

The FCMs were first run for the current situation of each farm type to assess their ability to represent the broad patterns of biomass production and biomass management strategies observed in the survey data. Each FCM represented one farm type and was composed of the same concepts and links, but differed in the weight associated to the links. Links between concepts were derived based on the characteristics of the farm types and their biomass management. In this calibration step, the weights were adjusted iteratively until the FCM outputs (i.e. the concept values at equilibrium) reflected the results of the biomass production and management analysis and the observed differences therein between farm types. FCM calculations were run over 100 iterations which allowed the values of concepts to reach an equilibrium (Kok, 2009). Concepts values at equilibrium can be positive or negative, indicating that the system affects the concept favorably or unfavorably, respectively, whereas the absolute value of a concept indicates the strength of the impact of the system on that concept. For example, if the concept 'livestock' stabilizes at a very small absolute value, it means that the farm type has no or very little livestock, and if its value is negative, it means that the farming system does not favor livestock production

Second, a sensitivity analysis was performed to test the robustness of each FCM independently and the FCM's sensitivity to variation in weight values. By identifying the links to which the farm performance concepts are most sensitive, potential levers for improvement were revealed. The analysis followed the One

Factor At Time (OFAT) approach, consisting of varying the value of one weight in each simulation of the FCM to check its effect on the outputs. In each simulation, the value of one weight was varied from -25% to +25%. The mean relative change in the value of each concept was used for analysis.

2.2.5.2 Scenario analysis

Two scenarios were developed based on the focus group discussions, survey data analysis and literature. The scenarios were analyzed with the fuzzy cognitive maps representing the farm types. The first 'residue-contract' scenario was plausible in current system settings and required that farmers mutually agreed on biomass management. This scenario implied that livestock from one farm that graze on another farm's residues left on the fields, are parked day and night on that particular field and return all the manure to the field. This type of contract was mentioned by farmers in the focus group sessions and the household survey as a strategy to improve farm performance. However, it is not yet a frequent practice in our study area. In this scenario it was assumed, based on our knowledge of the farming system, that leaving crop residue on fields of subsistence farms would allow them to increase the amount of manure collected from market-oriented farms by one third. Therefore, the 'residue-contract' scenario was translated into (i) for subsistence-oriented farms, an increase of 0.33 of the value of the weight on the link between crop residue left on field and manure received from farms owning cattle and (ii) a decrease of 0.33 of the value of the weight between the cattle in the household and the amount of manure collected in market-oriented farms because part of the manure produced by owned cattle is deposited on fields of other farms. Details concerning the changes in the FCMs for each scenario are supplied in the supplementary materials (Table S3, Appendix 1).

The second 'diversification and policy' scenario is meant to explore potential effects of more drastic policy changes. Here we assumed that government subsidies would reduce the prices of external inputs for farmers (fertilizer, fodder, concentrate to feed livestock) by 30%, thus allowing a higher input use for all farm types. Currently, the Burkina Faso government provides a 50% subsidy on NPK and urea fertilizers. These subsidies target mainly maize and rice producers, but only a small fraction (38%) of them actually have access to the subsidized fertilizers (Coulibaly and Savadogo, 2020). In this scenario, we assumed that the access issue would be resolved and that all farmers would have access to subsidized inputs. We also considered that a 30% subsidy on external inputs (fertilizer, fodder, concentrate to feed livestock) is more realistic than a 50% subsidy which is currently only applied to fertilizer. In addition, this scenario aimed for more equitable outcomes across farm types by supposing that off-farm income of low resource endowed farms would double and that they would invest the extra income in farming activities. This last assumption was derived from the results of the statistical typology which revealed a similarly high importance of off-farm income for the farm type with a higher resource endowment in our sample. The 'diversification and policy' scenario was translated to the FCM through a 30% increase of the weight on the link between on-farm and off-farm income and the amount of fertilizer, concentrate and crop residue bought, to reflect that with the same amount of income more inputs could be bought due to price subsidies. In addition, the value of off-farm income was doubled for the low resource endowed farms.

In running both scenarios, a variation of 25% on the "risks" concept value was included to reflect the variability in farm production in response to rainfall variability. The variation rate was based on the actual coefficient of variation (23%, calculated from climate data from the 1964-2019 period) of the annual rainfall in the study area. To do so, for each run of FCM, a sequence of 20 values of the "risks" concept were generated by varying its value from -25% to +25% of the equilibrium value. This implied that for each scenario we computed 20 series of outputs per FCM. The average values as well associated standard deviations across the 20 runs were presented.

2.3 Results

2.3.1 Farm diversity

2.3.1.1 Statistical based typology

The hierarchical clustering applied to the PCA revealed four farm types in the study area.

The subsistence-oriented crop type (SOC, n = 85 households) was the dominant type, with on average 71% of their on-farm revenue coming from cropping activities. The total cultivated area was 2.3 ha on average with 7% rented and 28% dedicated to cash crops (sesame, peanut, Bambara nut). Households in this type produced grain mainly for consumption and had the second lowest annual total income (94 035 FCFA). Diversification of income was relatively important as 25% of their total revenue was earned from off-farm activities (e.g. gold mining, commerce and handicraft jobs).

The subsistence-oriented livestock type (SOL, n = 79 households) cultivated on average 1.65 ha of which 19% was rented in. Compared to the SOC households, the herd size was not statistically different (3 TLU – Tropical Livestock Unit –vs 2.6 TLU), with small ruminants representing 50% of the herd. Livestock production contributed to 56% of the on-farm income, but the SOL type had the lowest annual total income (82 799 FCFA). Income diversification was less important as in SOC type, with 18% of the total revenue coming from off-farm activities.

The third farm type was the market-oriented and diversified type (MOD, n = 51 households). This type had the largest cultivated area (3.5 ha), renting only 3% of their land. With a herd size of 4.6 TLU and a contribution of 76% of on-farm income, livestock production was more important than for the two subsistence types. Cash crops (sesame, peanut and cowpea) production represented 35% of the cultivated area. The household size was larger than for SOC and SOL (12 people vs 8 for SOC and 7 for SOL). The annual total income of MOD farms was the highest (957 225 FCFA) and most diversified in terms of revenue, of which 54% came from off-farm activities.

The last farm type was the land constrained livestock type (LCL, n = 10 households). This type corresponded to the Peulh ethnic group, specialized in cattle production with a much larger herd size (32 TLU) than the other types. Contrastingly, crop production was limited with only 1.5 ha cultivated and 50% of that area rented in. This farm type came second in terms of total income with 612 100 FCFA per year but it had the highest annual on-farm income (522 100 FCFA). LCL type was least diversified with off-farm income contributing only 9% of the total income. LCL households had the largest family size with 15 members on average. Only few LCL farms were investigated because (1) they are a minority ethnic group only present in Yilou and (2) the budget allocated to the survey did not allow to investigate more of them.

Both villages were dominated by subsistence-oriented farms (68% for Yilou and 85% for Tansin). Yilou had more MOD farms than Tansin (26% vs 15% respectively). LCL farms (only present in Yilou) represented 6% of the surveyed farms in that village.

2.3.1.2 Comparing statistical and participatory typologies

Four main types of farms were identified by farmers during the focus group discussions: agro-pastoralist, pastoralist, revenue-diversified and subsistence-oriented (Figure 2.2). Farmers divided each type (except the subsistence type) into three subgroups according to resource endowment (Figure 2.2). The main criteria of classification included the contribution of off-farm activities to the total revenue, number of cattle in the household, the total cultivated area, and the number of tricycles, motorbikes and carts in the household. Only two variables used in the statistical typology were deemed important by farmers: total cultivated area and the contribution of off-farm revenue to the household income. Instead, other wealth indicators were used such as the number of motorbikes and tricycles. Livestock was used as a discriminant variable in both typologies but with different purposes. In the statistical typology the total herd size was considered as an indicator of the structure of the farm, while farmers considered the number of cattle as an indicator of the wealth and production goal of the farm.

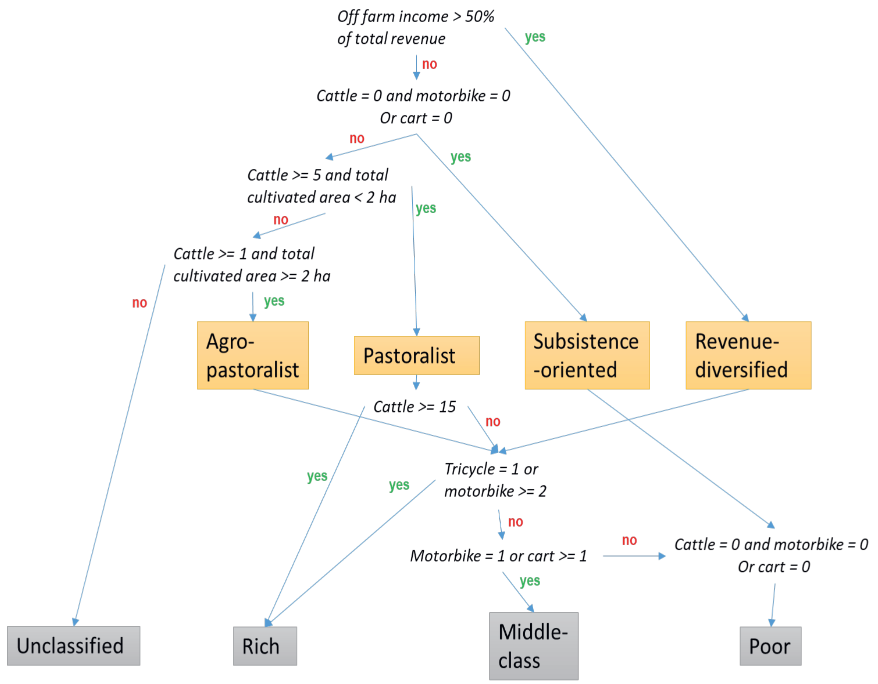


Figure 2.2: Rule-based typology, established using information from focus group discussions with farmers.

The participatory typology agreed well with the statistical typology for the subsistence-oriented farms (Figure 2.3). Indeed, 90% of the farms classified as subsistence-oriented by farmers were also classified statistically as subsistence-oriented (SOC or SOL) farms (Figure 2.3). The agro-pastoral farms were distributed into three statistical types, mainly as SOC and SOL and less so as MOD. The pastoralist type was generally classified as SOL or LCL by the statistical approach. There was a poorer match (57%) between revenue-diversified and MOD farms. The remaining revenue-diversified farms corresponded to SOC and SOL types. Thirty-three farms could not be classified according to the rule-based typology, because their characteristics did not fit the rules used for the participatory typology (Figure 2.2). Most of the unclassified farms (91%) corresponded to subsistence-oriented farms based on the statistical typology. Therefore, based on the overall fair match between statistical and participatory (rule-based) typologies and because all farm types could not be classified using the participatory typology, the statistical typology was used for the analysis of biomass production and management as well as FCMs design.

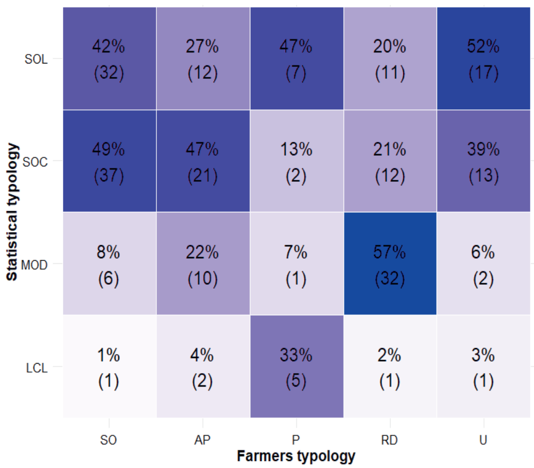


Figure 2.3: Comparison between statistical and farmers' typology. The percentages represent the proportion of a farm (farmers' typology) corresponding to a certain statistical farm type. In parenthesis are the number of farms. SO = subsistence oriented; AP = Agro-pastoralist; P = Pastoralist; RD = Revenue-diversified; U = Unclassified. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock.

2.3.2 Biomass production and management by the different farm types

Sorghum was the only crop cultivated by all farm types in the study area. Hence it was used as the basis for our analysis on crop residue production and management. Sorghum grain yield varied from one farm type to another. The highest yield (1853 kg/ha) was reported by LCL farms while the lowest (972 kg/ha) by SOC farms. Sorghum residue produced at farm level displayed important differences across farm types. MOD farms produced most sorghum residue (3893 kg/farm), followed by LCL (3144 kg/farm) and SOC farms (2492 kg/farm), with SOL farms (2306 kg/farm) producing the least. Whereas the proportion of harvested crop residues varied slightly between farm types (from 88 to 95% of total production for MOD and SOC farms respectively) the amount of residue harvested per animal unit was similar in MOD (1135 kg/TLU), SOC (1198 kg/TLU) and SOL (1351 kg/TLU) farms. As LCL farms had many animals to feed from a small cultivated land area, the amount of residue harvested per unit of animal was negligible (96 kg/TLU). Nevertheless, the amount of residue harvested per hectare ranged from 1989 kg/ha (for SOC farms) to 2617 kg/ha (for LCL farms) without statistically significant differences between types.

Sorghum residue use differed across farm types (Figure 2.4). The proportion of residue harvested to feed livestock was related to the herd size. Indeed, the subsistence-oriented crop farms (SOC), who owned fewer heads than other types, harvested the least while the land constrained livestock (LCL) farms, who specialized in cattle production, harvested the most. In general, sorghum residue uses were more diversified in subsistence-oriented farms compared to market-oriented farms. Crop residues were sold and used as fuel only by subsistence-oriented farms (SOC and SOL, Figure 2.4). For MOD and LCL farms, crop residue was either harvested and used as fodder or left in the field for grazing or mulching. SOC and SOL left less residue on fields and used their crop residue less as fodder than MOD and LCL.

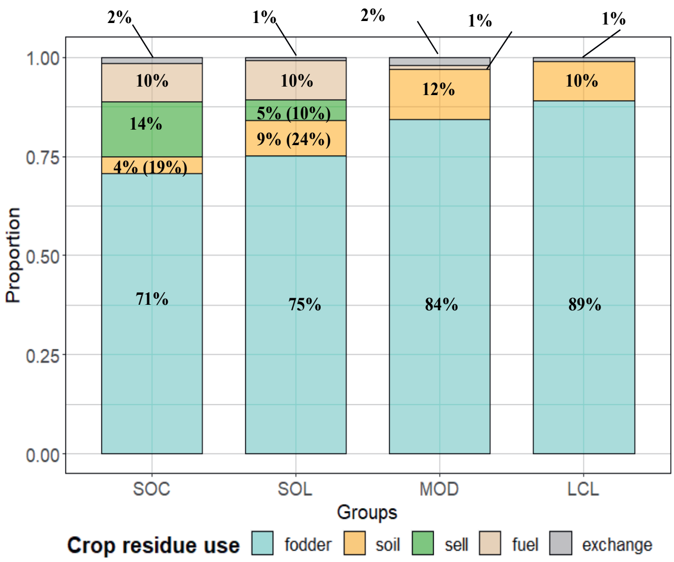


Figure 2.4: Proportion of total sorghum residue biomass that is used for different purposes. In parenthesis, the proportion of farms using their crop residue for a certain purpose. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock

Animal manure was one of the main organic inputs (apart from crop residue) for soil fertility management in the study area. The amount of manure applied per ha was inversely proportional to the total cultivated area. The manure application rate was highest for LCL farms keeping large cattle herds (Figure 2.5).

However, the total amount of manure applied per farm was not statistically different among the farm types. This was due to the large amount of manure collected from pasture land especially by subsistence-oriented farms owning less livestock.

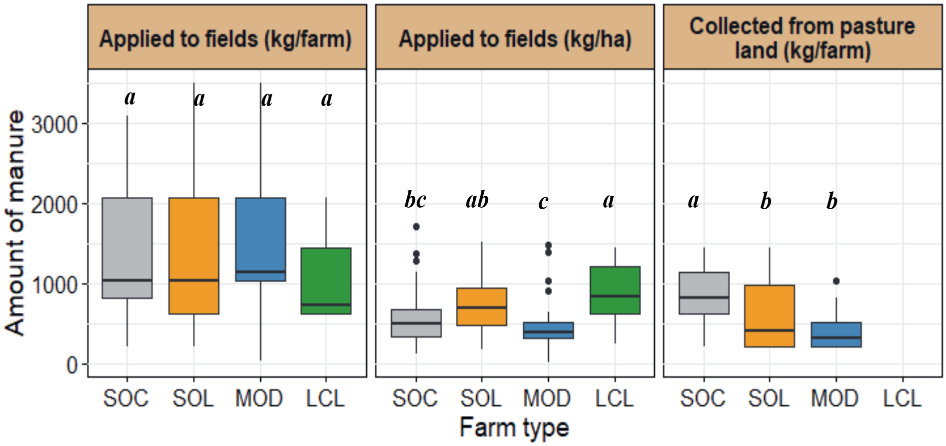


Figure 2.5: Amount of manure (dry matter) applied to fields and collected from pasture land by all farm types. Boxplots with the same letter are not significantly different at p=0.05. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock.

The proportion of farms importing crop residue (22%, 12%, 19% and 80%) bran (19%, 24%, 27%, and 30%) and concentrated feed (42%, 47%, 45%, and 100%) for livestock feeding varied between SOC, SOL, MOD and LCL respectively. On average, subsistence-oriented farms purchased more crop residue per unit of livestock (Table 2.2). Except for LCL farms who bought less, all farm types purchased a similar amount of bran and concentrate feed per unit of livestock. Farmers rarely bought new animals. Purchasing grain to feed the family was rare for all farm types except LCL which bought a significantly higher amount of sorghum grain per capita (Table 2.2). In terms of biomass outflow, only SOC and SOL farms sold their residue, with SOC farms selling the most (Table 2.2 & Figure 2.4). Sorghum grain selling was only done by SOC farm type but the proportion of produced grain that was sold was usually almost none. Compared to sorghum, a higher proportion of sesame, peanut and cowpea grain was sold by SOC, SOL and MOD even if the amount sold per capita was negligible. LCL farms did not report any grain selling, but were more engaged in cattle selling than other types. SOL, MOD and LCL farms sold similar numbers of small ruminants, whereas sales of other livestock were rare. In general, absolute numbers of animals sold were larger for LCL farms, but MOD followed by SOL farms sold a higher proportion of their herd.

Table 2.2: Biomass (crop residue, grain, bran and concentrate feed) inflows and outflows in farm types (mean ± standard deviation). Variable values with the same letter are not significantly different between farm types. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock.

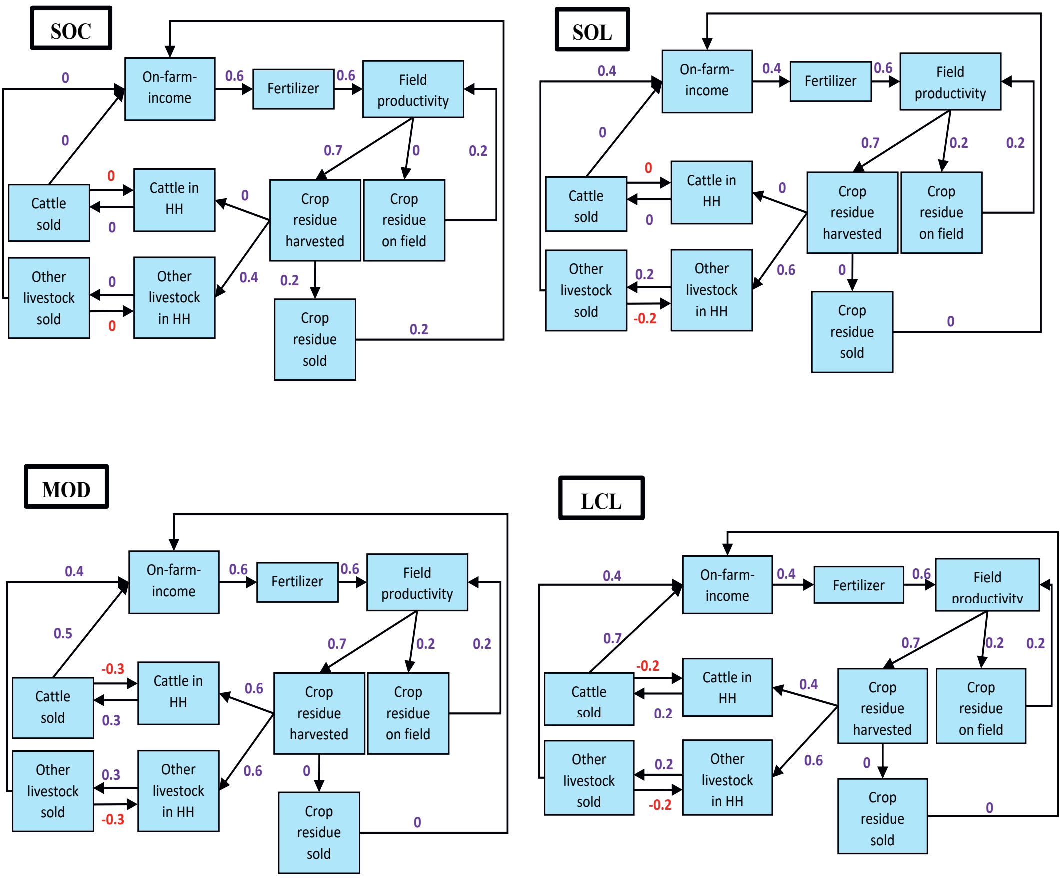
	SOC	SOL	MOD	LCL	Units
Inflow					
Sorghum residue bought	54±145b	44±177b	44±271b	24±37a	kg/TLU
Bran bought	18±65a	17±43a	62±182a	8±21a	kg/TLU
Concentrate feed bought	30±49a	61±172a	44±90a	30±30a	kg/TLU
Cattle bought	0±0.3b	0.1±0.3ab	0.2±0.6a	0±0b	TLU
Small ruminants bought	0±0.1ab	0±0.1a	0±0b	0±0b	TLU
Poultry bought	0±0ab	0±0b	0±0a	0±0b	TLU
Donkey bought	0±0.2a	0.1±0.2a	0±0a	0±0a	TLU
Sorghum grain bought	8±16b	6±15b	35±179b	349±1003a	kg/capita
Cowpea grain bought	0±0a	0±3a	1±7a	0±0a	kg/capita
Peanut grain bought	0±0a	0±0a	0±0a	0±0a	kg/capita
Outflow					
Sorghum residue sold	229±1170a	3±14b	0±0b	0±0b	kg/TLU
Cowpea residue sold	13±118a	0±0a	0±0a	0±0a	kg/TLU
Peanut residue sold	2±20a	0±0a	0±0a	0±0a	kg/TLU
Sorghum grain sold	2±20a	0±0a	0±0a	0±0a	kg/capita
Cowpea grain sold	9±19a	6±35b	6±27ab	0±0b	kg/capita
Peanut grain sold	5±18a	2±7b	3±16b	0±0b	kg/capita
Sesame grain sold	3±7a	1±2b	4±12a	0±0b	kg/capita
Proportion of sorghum grain sold	1±11a	0±0a	0±0a	0±0a	%
Proportion of cowpea grain sold	38±44a	16±31b	21±38b	0±0b	%
Proportion of peanut grain sold	67±46a	33±45b	51±43ab	-	%
Proportion of sesame grain sold	88±23a	63±38b	57±49ab	-	%
Cattle sold	0±0.2c	0.1±0.3c	0.4±1.2b	1.8±1.4a	TLU
Small ruminants sold	0±0.1b	0.2±0.3a	0.4±0.4a	0.5±0.7a	TLU
Poultry sold	0±0b	0.1±0.6b	0.3±1a	0±0.1b	TLU
Donkey sold	0±0a	0±0.1a	0±0a	0±0a	TLU
Proportion livestock sold	6±24c	17±30b	25±27a	8±7ab	%

Biomass exchange between households was rare. Out of the 225 households included in the analysis, only eight reported to exchange biomass with others. The most frequently observed biomass exchange concerned crop residue against manure and vice versa. In only one case, crop residues were exchanged for labor (land tillage). Farmers of all types kept livestock that are owned by other households. By keeping other farms' livestock, they benefitted from the animal labour force, manure, any new-borns and part of the revenue in case the animal is sold. The benefit for the household borrowing its animal was a reduction in the labor and feed required to take care of the animal. It was also seen as a gesture of generosity towards the receiving household. However, the average proportion of 'foreign' animals was generally low at a maximum of 8 % on average in LCL farms.

2.3.3 Farm level modelling using fuzzy cognitive mapping

2.3.3.1 FCM calibration

Based on a generic FCM describing the farm systems in the region, four farm type-specific FCMs varied only by the value of their weights, in line with the main characteristics of each farm type (Figure 2.6).



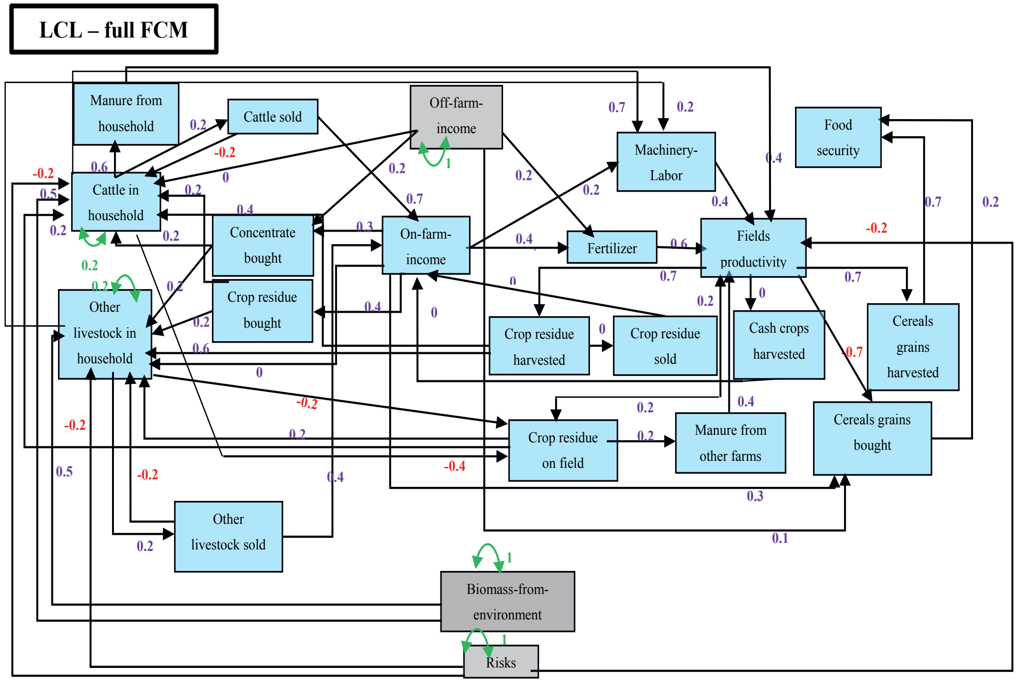


Figure 2.6: (SOC, SOL, MOD, LCL) Illustration of part of SOC, SOL, MOD and LCL FCM respectively, showing key differences between them and the complete FCM of LCL farm type (LCL – full FCM). Blue boxes are concepts (variables) and grey boxes are the drivers of the system. Black arrows (directed edges) represent the impact of one concept on another while green arrows refer to self-reinforcement of drivers or concepts. The FCMs were based on findings of the survey data. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock. HH= Household.

After calibration, we obtained values of the concepts at equilibrium that reflected the pattern of biomass management for the four farm types (Figure 2.7). For example, the FCM results for the SOC farm type revealed limited cash crop, cereal grains and livestock production. SOL farms had even less cash crop production, cereal grain harvested and crop residue production. Cash crop production and livestock selling being important for MOD farms, their equilibrium value of on-farm income was large. In addition, LCL had the largest concept values for the livestock herd and manure produced (Figure 2.7). Livestock selling was important and LCL farms had the highest on-farm income. The FCM results also suggested that for MOD and LCL types, biomass management did not allow crop residue to be left on the field, because of livestock grazing and limited crop residue production compared to the herd size. On the contrary, the SOC and SOL types had the possibility of mulching even if the amount of residue potentially left on the field was small.

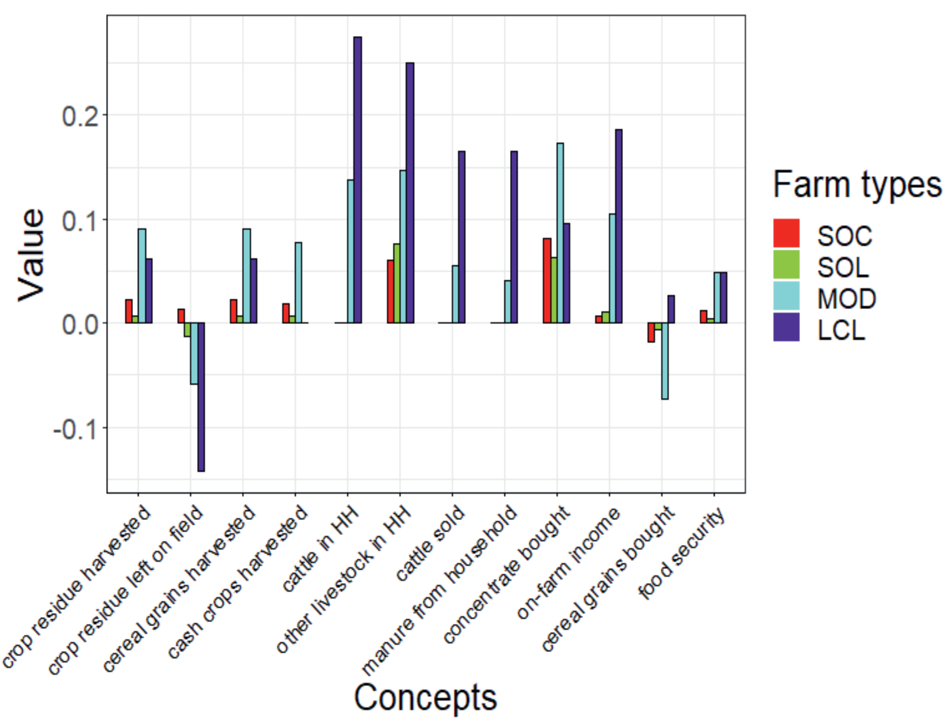


Figure 2.7: Values of key concepts in the FCM for the baseline scenario per farm type. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock. HH= Household.

2.3.3.2 Sensitivity analysis

Variation in only seven links (weights) out of the total 55 links resulted in significant changes in the FCMs outputs (Figure S6, Appendix 1) for all farm types. Field productivity was a key concept that appeared in three of the seven links to which the FCMs were sensitive. These links related field productivity with fertilizer, machinery/labor and risks. Further, the essential role of off-farm income was revealed through the links between the latter on the one hand and fertilizer and machinery/labor on the other hand. The biomass from environment was also a key concept in LCL and MOD farms as its availability to cattle affected both livestock and crop production, on-farm income as well as grain and concentrate inflows (Figure 2.8A). A similar remark applied to SOL type for the link between biomass from environment and – livestock (except cattle) (Figure 2.8B). The fertilizer – field productivity link is the only biophysical link affecting all farm types' crop production, concentrate feed (except LCL) and grain inflow (Figure 2.8C). The machinery labor – fields productivity link mainly influenced grain and residue harvested, and to a lesser extent grain inflow and food security in the household, especially for SOL type. The latter were also the most affected by the link between off-farm income and machinery labor (Figure 2.8D and Figure 2.8F). The off-farm income –

fertilizer link also caused important variation in the FCM outputs especially for SOL and SOC types (Figure 2.8E). Variation in the weight of the risks – fields productivity link resulted in significant impact on the cropping subsystem as well as grain inflow for all farm types (Figure 2.8G), especially for the subsistence-oriented ones.

The analysis pointed out the importance of mechanization and labor as well as off-farm revenue on the studied farm systems. The results also suggested that risks related to climate variability, pests and diseases, would mainly affect the subsistence-oriented farms, which dominated our study area.

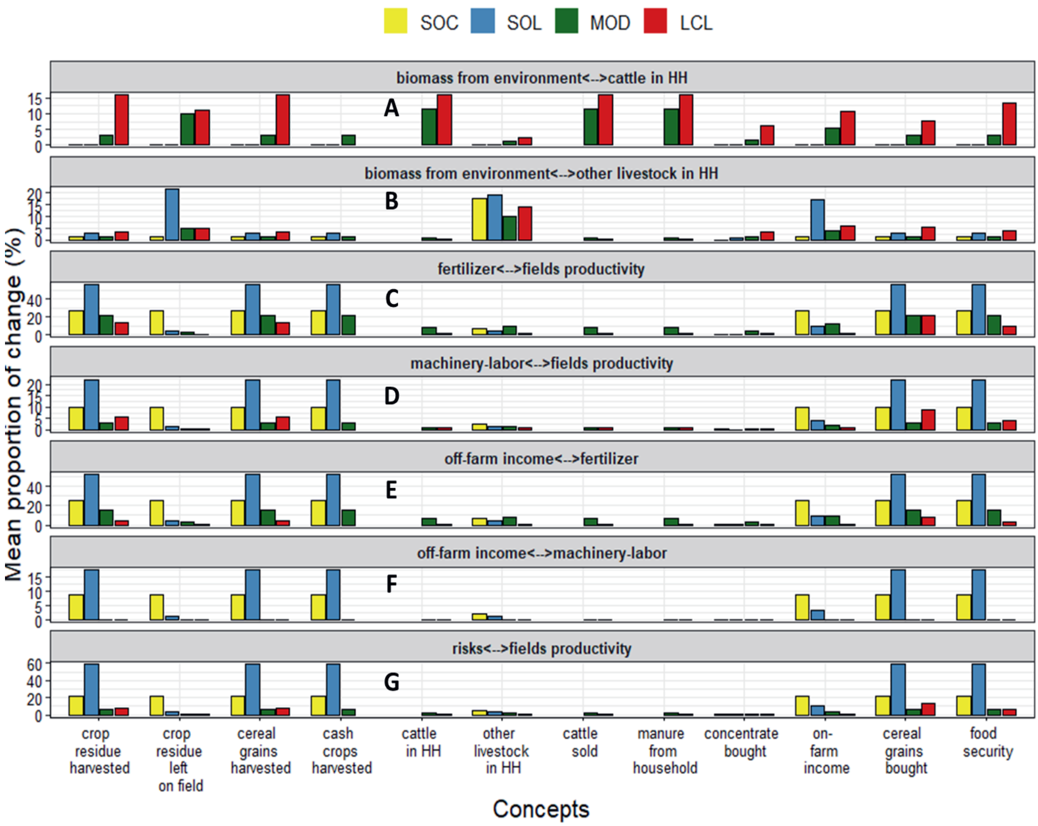


Figure 2.8: results of sensitivity analysis showing mean proportion of change in concepts values as a result of variations of the most sensitive links all farm types have in common. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock. HH= Household.

2.3.3.3 Scenario analysis

The 'residue-contract' scenario was slightly beneficial for the SOC farm type in terms of manure gain from other farms, grain and crop residue harvested (Figure 2.9). The performance of the SOL farm system was not affected by this scenario. The 'residue-contract' scenario was unfavorable to MOD and LCL farms, because by leaving part of the manure on other farms, less manure was available for their own cropland, which negatively impacted their crop production.

The 'diversification and policy' scenario benefited all farm types, especially SOC and SOL farms, and effects were more pronounced than for the 'residue-contract' scenario (Figure 2.9). Indeed, in this scenario, we assumed off-farm income of SOC and SOL would double and they would reinvest that extra revenue into their farm. Together with the input subsidies for all farm types, this resulted in higher crop production and on-farm income. Livestock production in all farm types also benefited from the price policy because crop residue production increased and concentrate feed was subsidized. The large variation around the average concept values (Figure 2.9), resulting from varying the risk level value by 25%, illustrates that the effect of a policy change drastically differed when weather or other hazards occurred.

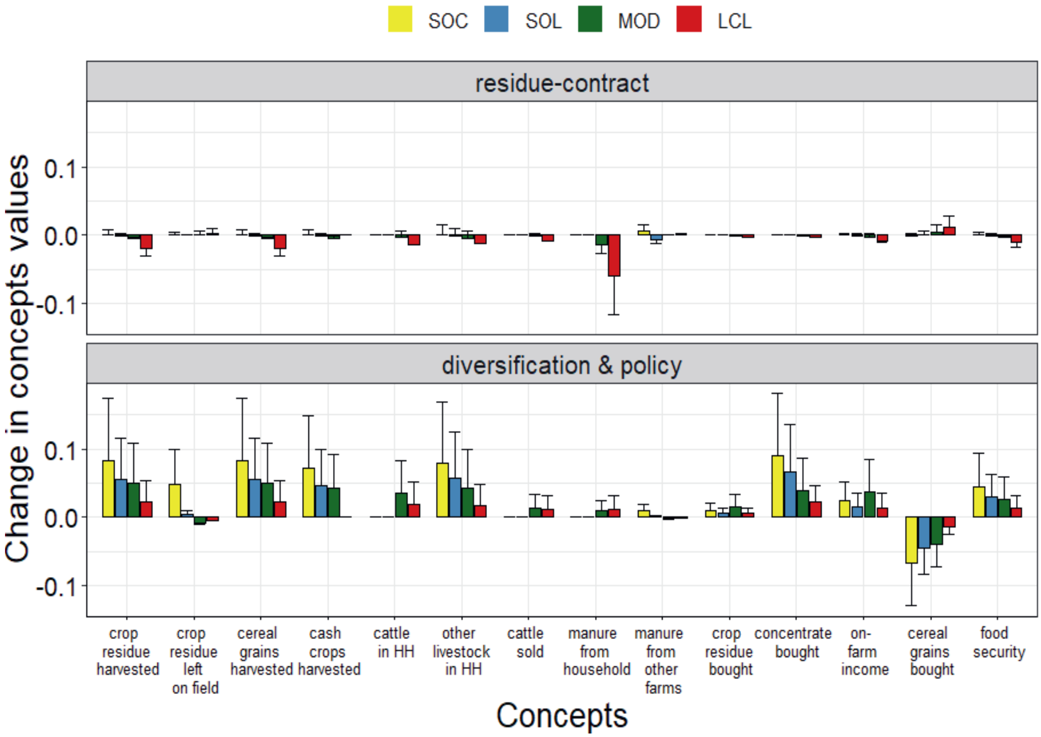


Figure 2.9: Change of key concepts values as compared to the baseline for the 'residue-contract' and the 'diversification and policy' scenarios for all farm types. Error bars are standard deviations resulting from the variation in risks. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock. HH= Household.

2.4 Discussion

2.4.1 Farm diversity

Our statistical typology was oriented towards resource endowment and production goals allowing us to capture the diversity of farms in terms of assets and livelihood strategies. Our statistical typology differed from the one developed by Diarisso et al. (2016) in the same area based on a survey conducted in 2012. This previous typology was oriented on structural characteristics and farm production goals and used different discriminating variables from ours. Differences with respect to the cultivated area, the herd size and the proportion of land dedicated to cash crops confirm that statistical typology results depend on researchers' objectives and that farm characteristics can possibly change over time (Alvarez et al., 2018). The most discriminating variables in our statistical typology included the total cultivated area, the herd and the household size, the proportion of cultivated land rented in, off-farm income share in the total revenue and the small ruminant ratio in the herd. Analogous variables were used by Ganeme et al. (2021) in a similar area in semi-arid Burkina Faso. In addition, they used small equipment which was also mentioned by farmers in the focus group discussions. Our participatory typology was oriented towards wealth and orientation in terms of crop and livestock production. While discriminating variables used in the statistical typology differed from the ones in the participatory typology, we found an overall fair match between both approaches. Similar results were found by Berre et al. (2019) and Kuivanen et al. (2016) between statistical and expert-based and participatory typologies in Ethiopia and Ghana respectively. However, the criteria and associated thresholds used in the participatory typology failed to classify a significant proportion (15%) of investigated households. This is potentially the consequence of averaging the threshold values for each criteria from several focus group discussions. It also points out the subjective aspect of criteria and thresholds used by farmers. Confronting the statistical typology to farmers' perceptions increases the legitimacy of the former and its accuracy in terms of describing the actual farm diversity (Kumar et al., 2019; Thar et al., 2021), which was deemed acceptable in this study based on the fair agreement between the two typologies (Figure 2.3). The characterization of farming system diversity is a useful first step in tailoring solutions for improved crop and livestock production (Descheemaeker et al., 2019). Associating farmers to this first step of typology construction builds a strong basis that leads to credible, relevant and legitimate participatory research (Falconnier et al., 2017; Richardson et al., 2021).

Biomass management varied from one farm type to another as shown also in other studies of mixed crop-livestock farming systems in sub-Saharan Africa (Diarisso et al., 2015; Valbuena et al., 2015). Inflows of crop residue, concentrate feed and grain in the household was driven by the cultivated land size, confirming the importance of the latter as a determinant of biomass management (Duncan et al. (2016)), and a capital enabling farmers to meet food and feed requirements. As also noted by Diarisso et al. (2015), the larger the livestock herd, the more likely the farm collected crop residue in order to feed the livestock. In addition, crop residue selling was not frequently reported and mainly observed in SOC farms, who owned the smallest herds of all types. Indeed, the herd size was inversely related to the proportion of sorghum residue sold and positively related to the proportion of sorghum residue left on field. The positive relation between crop residue use as fodder and herd size was also found by Jaleta et al. (2015) in maize-based farming systems in Ethiopia. Across all farm types, crop residue was mainly aimed at livestock feeding, mulch and household needs. This is typical of regions with moderate to low crop residue production, moderate livestock feed requirements and few alternative biomass resources (Valbuena et al., 2015). Indeed, crop residue scarcity induces a tradeoff between the use of the residue as mulch or as fodder (Tittonell et al., 2015). Both uses have the advantage of improving nutrient cycling in the farming systems (Baudron et al., 2015; Diarisso et al., 2015) and the actual crop residue allocation by farmers depends on their orientation, as shown in Figure 2.4. When deciding on the use of crop residues, farmers usually prioritize their livestock as it contributes to easing labour for land preparation, generates income and food, and, through manure production, also contributes to soil fertility. Indeed, at least in the short-term, this strategy is more profitable for livestock keepers (Rusinamhodzi et al., 2015).

Biomass (crop residue, manure and livestock) exchange was not common in the study area despite the complementarity between crop and livestock oriented farms. This could be explained by the scarcity of biomass, and crop residues in particular, and the lack of familiarity between livestock oriented farms (LCL), belonging to an ethnic minority, and other farm types (Abroulaye et al., 2015; Robert, 2010) .

2.4.2 Levers for improved biomass management

Based on the farm type description, we built four FCMs that allowed to explore farm system functioning and biomass management, as well as the diversity therein. Similarly, Aravindakshan et al. (2021) and Murungweni et al. (2011) built FCMs per farm type, and used them to explore their farming systems regarding water management and policy, and livelihoods responses to climate change respectively. The sensitivity analysis indicated that the farm systems in our study area were relatively sensitive to the availability of biomass from the environment, to labor availability and fertilizer efficiency in the cropping sub-system, to the impact of various hazards on crops and livestock, and to the contribution of off-farm income. Indeed, releasing labor constraints through mechanization and releasing cash constraints for investments in agricultural inputs through income from off-farm activities are well-known levers for better farm production (Giller et al., 2021; Sims et al., 2016). This study also revealed type-specific insights about levers, strategies and potential effects on farm performance. Indeed, depending on the investigated farm type the key levers to improve biomass production and management differed. Subsistence-oriented farm systems were the most sensitive to income diversification and investment in equipment, hence they could be the ones benefiting the most from these changes (Figure 2.8). Moreover, improvement of fertilizer use efficiency is likely to benefit subsistence-oriented farms most strongly even though its impact would be felt in all farm types (Figure 2.8). This improvement can be achieved through appropriate farm management (e.g. cereal-legume rotation, organic amendment, stone bunds, etc.) and fertilizer application techniques, as shown by various studies in Burkina Faso (Bado et al., 2007; Ouattara et al., 2018; Zougmoré et al., 2004a). However, many of these interventions require additional labor (Dahlin and Rusinamhodzi, 2019) which is often not available at the farm level. Therefore, the combination of income diversification, investment into equipment and appropriate farm management could lead to enhanced crop and livestock productivity in all farm types (Falconnier et al., 2018). For households keeping significant heads of livestock, especially cattle, availability of fodder in pastureland land is critical to meet livestock feeding requirements and is the main reason behind seasonal transhumance (Kiema et al., 2014). Improved forage production and management options, such as the cultivation of high-quality forage (dual purpose legume and cereals), tree-cereal-legume intercropping, recommended fertilizer and manure application rate, and silage of forage has the potential to reduce transhumance duration and therefore increase manure availability for crops (Balehegn et al., 2021; Paul et al., 2020).

When considering levers for better production, the vulnerability of farming systems to hazards should not be overlooked (Falconnier et al., 2020). Indeed, the negative impact of hazards (especially related to climate variability) on farming systems has been previously demonstrated in Burkina Faso (Barbier et al., 2009; Douxchamps et al., 2016; Fraval et al., 2020). In addition, the vulnerability of farms to climate variability and change is not uniform among smallholder farmers. Indeed, the intensity and diversity of crop and livestock production as well as the degree of income diversification are determinant factors regarding farmers' resilience (Descheemaeker et al., 2018; Williams et al., 2020).

Scenario analysis further allowed to explore the window of opportunity based on two scenarios, which contrasted in their immediate plausibility in the current farming systems. The most plausible 'residue-contract' scenario did not positively impact farm performance except for the SOC farms, who did not keep a lot of animals and sometimes sold their residue. This scenario negatively influenced crop and livestock production especially for large cattle owners (LCL) because part of their manure would be left on other farms hence reducing the amount that is potentially applicable to their own fields. Similarly, Andrieu et al. (2015) and Berre et al. (2021), who explored the use of crop residue as a private resource at village scale in Burkina Faso, found that cattle owners were less favored in this scenario. Contrastingly, the more optimistic and drastic 'diversification and policy' scenario suggested a positive impact on crop and livestock production associated with price reduction of external inputs and higher off-farm income for SOC and SOL farms. The assumption of doubling the off-farm income for subsistence-oriented farms was driven by the observation that the MOD type had a higher share of off-farm income, demonstrating the possibility for farmers to access such opportunities (i.e. owning a shop, gold mining, handicraft job). The LCL farms benefited the least from this scenario because their off-farm revenue did not change and with their limited access to land they benefited less from the fertilizer price subsidy. Moreover, LCL farms relied heavily on free grazing and transhumance in the dry season to feed their animals (Houessou et al., 2020) and this could explain why the feed input subsidy did not positively affect their livestock production. However, higher levels of inputs did not necessarily translate into higher production due to risks related to climate and other hazards (Rigolot et al., 2017b). Indeed, even if there is a strong potential for higher level of inputs to increase crop and livestock production in SSA, uncertainties in future climate characteristics makes the potential benefits unclear (Falconnier et al., 2020; Tui et al., 2021). Overall, the small scope for improvement from adjusting management practices strongly contrasted with the large potential impacts from higher-level interventions that change the socio-economic context of the farming systems, as was found for southern Mali using a mechanistic model in a scenario analysis (Falconnier et al., 2018). Indeed, these authors demonstrated that farming systems transformation towards sustainable production and food security relies on policy interventions towards income diversification, equipment and farm inputs.

In line with the need to tailor levers for improvement to the context of different farm types, policy interventions aiming at transforming farming systems should consider local diversity in farming systems (Yesuf et al., 2021). Indeed, agricultural interventions in sub-Saharan Africa generally benefit better-off farms with subsistence farms often experiencing no considerable improvement (Thuijsman et al., 2022). In line with other literature, our findings indicate that more inclusive policies aggregate elements that specifically benefit different farm types. Firstly, the promotion of alternative off-farm employments for subsistence-oriented farms can incite them to either move out of farming or increase their capacity to invest in their farms. This could improve their level of food security (Falconnier et al., 2018) and present a way out of poverty (Giller et al., 2021). Secondly, market-oriented farms could benefit from policies facilitating access to local, urban and regional markets (Wichern et al., 2017). Finally, farms oriented on intensive livestock production would benefit from policies targeting improved forage production and storage (Balehegn et al., 2021; Yesuf et al., 2021).

Even though FCM revealed promising levers to improve biomass production and management, two important limitations of the FCM method include that (1) it is not spatially explicit and (2) it is not dynamic over time. For example the spatial dynamics of livestock moving in and out of the village, which plays a key role in soil fertility management at landscape scale (Berre et al., 2021), could not be considered. In addition, in the ‘residue-contract’ scenario we did not consider the number of contracting and receiving farms in the village. To overcome these limits, future work can combine the FCMs findings with agent-based models, in which space and time can be very well represented (Giabbanelli et al., 2017; Mehryar et al., 2019).

2.5 Conclusion

We investigated biomass management in relation to farm diversity in the biomass-scarce environment of semi-arid Burkina Faso. Farm diversity was explained by differences in resources endowment and production goals. Based on a comparison with a participatory typology we conclude that our statistical typology gave a fair representation of the diversity in the study area as perceived by farmers, and hence could be used as a basis for the rest of our analysis. Biomass management strategies varied between farm types and were mainly driven by the total cultivated area and the herd size. Fuzzy cognitive mapping was used to explore levers for better biomass production and management through sensitivity and scenario analysis. We found that subsidies on major farm inputs (fertilizer, fodder, concentrate to feed livestock) combined with higher off-farm revenue for subsistence-oriented farms could lead to better production. In contrast, the exchange of residue with manure between livestock and non-livestock owners would not be beneficial for most farms. Our study showed that a semi-quantitative technique, that is not data demanding, can represent farm diversity and can be used to explore levers for better biomass management both in technical (scenario 1) and institutional (scenario 2) dimensions. As such, it is a useful basis for exchange with different types of stakeholders, including farmers and higher-level decision makers, as it can identify interventions that are tailored to diverse farm types. However, further investigation is needed to quantify the expected impacts on crop and livestock production. Such research should be conducted using an interdisciplinary framework in collaboration with farmers in order to co-design appropriate individual and collective farm management options and policy recommendations.

2.6 Acknowledgement

The present study is part of a PhD thesis included in the 3F (Feed the soil to Feed the cow and Feed the people) project funded by the McKnight foundation. This article could not be written without the help of famers and local authorities of the villages of Tansin and Yilou.

3 Can low-input agriculture in semi-arid Burkina Faso feed its soil, livestock and people?[‡]

[‡] This chapter was published as:
Assogba, G. G., Berre, D., Adam, M., & Descheemaeker, K. (2023). Can low-input agriculture in semi-arid Burkina Faso feed its soil, livestock and people?. European Journal of Agronomy, 151, 126983.

Abstract

Agriculture in semi-arid Burkina Faso is dominated by mixed crop-livestock smallholder farms with limited investment capacity in production factors, such as improved seeds, fertilizer and equipment. Hence, to make a living, farmers try to make the best use of available resources based on principles of agro-ecology, including crop diversity and nutrient and biomass recycling. We investigated farm-level management of resources (soil, crops and livestock) through time to assess whether the current management options were able to sustain crop and livestock production and fulfil household food requirements. We ran a one-year detailed farm monitoring campaign in collaboration with 22 volunteer farmers representing the diversity of the farming system in our study area. We quantified inputs and outputs in the cropping system (177 fields) for one rainy season. In addition, the weekly dynamics of crop residues left on field were quantified. Moreover, inflow and outflow of resources at farm level were quantified weekly. The cropping system was characterized by a negative nitrogen balance of about 12 kg N/ha/year, with market-oriented farms and large livestock owners having the most negative balance. Legumes grown (sole and intercropping) contributed to alleviate the nitrogen depletion by adding 15 kg N/ha/year to the nitrogen inputs through atmospheric fixation. However, cereal-legume intercropping did not significantly reduce the nitrogen deficit in comparison to sole cereal cropping mainly because of the small proportion of legumes (8%) in intercropped fields. Livestock grazed crop residues left on the soil (739 kg dry matter/ha on average) at a rate of 26 -76 kg/ha/week, thus strongly reducing the potential for mulching in the region. Livestock protein requirements were rarely met from farm-produced feed with average feed gaps ranging between 40 and 89% of the daily requirements for small and large herd keepers respectively. Large livestock (cattle) owners relied on transhumance during the rainy season, grazing and frequent purchase of crop residues and concentrates to feed their livestock. We estimated that grazed biomass provided on average at least 73 and 58% of metabolizable energy and protein feed requirement of livestock respectively. Concerning food availability, the amount of grain produced was generally enough to fulfil household energy requirements (89-175% of required energy, in kcal), even if households with higher people to land ratio were not self-sufficient. We concluded that the current farm management, even if it provides enough food for the majority of investigated farms, results in soil fertility mining and poor crop livestock production and integration. Our detailed farm data indicate that an appropriate diversity of crops and a better integration of legume crops in the cropping system, associated to improved manure and forage management is needed to sustain crop and livestock production.

Keyword: farming system, crop-livestock, biomass, agro-ecology, food security, sub-Saharan Africa.

3.1 Introduction

The population in sub-Saharan Africa (SSA) is projected to reach 2 billion by 2050, representing an 82% increase compared to the 2022 population (United Nations Department of Economic Social Affairs, 2022). For the same time horizon, the Food and Agriculture Organization (FAO) estimates that 12% of the population will be undernourished if the actual food production system does not improve (FAO, 2022). Indeed, despite a slight increase over the past years in yields of major crops (maize, sorghum, millet, cassava) on the continent, food insecurity is still prevalent (FAOSTAT, 2022). Also in semi-arid Burkina Faso, important yield gaps in the cropping and the livestock system (Henderson et al., 2016b) have resulted in significant proportion of households being food insecure (Fraval et al., 2020).

In the semi-arid areas of West-Africa, crops and livestock are combined in the typical mixed crop-livestock farming systems. This system offers the opportunity of increased crop and livestock production compared to specialized crop or livestock farms, through enhanced nutrient cycling at farm level (Duncan et al., 2013). However, the current crop and livestock productivity in the area is far below the potential mainly because of insufficient inputs (Henderson et al., 2016b; Powell et al., 2004), which further limits the mutual benefits between the crop and livestock enterprises. This manifests itself through a lack of crop residues to maintain soil fertility (with mulch) and feed livestock (Assogba et al., 2022) and further results in declining soil fertility (Cobo et al., 2010) . Therefore, farmers combine crop diversity with nutrient and biomass recycling, in the limit of available resources, to make a living (Giller et al., 2021).

Whereas in theory, several options can improve crop and livestock integration and agricultural production, in practice, only few of those are used by farmers (Arslan et al., 2022). Many studies investigated specific farm management options (e.g.: soil fertility management, spatial and temporal arrangement of crops, livestock feeding strategies, etc.) in relation to some or all components of the farm system (Adams et al., 2016; Ajayi, 2011; Falconnier et al., 2016; Rufino et al., 2011). However, farm management is quite diverse and dependent on resources and production goals (Berre et al., 2022). Hence there can be a mismatch between proposed options to improve components of the farm system and farmers' reality, leading to poor adoption (Takahashi et al., 2020).

Therefore, in order to propose options that are relevant and feasible for different types of farmers, there is a need to better understand the impact of current management in the different farm components on the overall farm, crop and livestock production. To reach that objective, empirical observations are needed at field and farm scale. Indeed, a combination of quantitative and qualitative observations allows a better understanding of factors influencing farmers' decision-making and resource use efficiency. In semi-arid West-Africa, several studies already quantified both field and farm scale resource use efficiency (Diarisso et al., 2016; Diarisso et al., 2015; Ichami et al., 2019). However, these studies often focused on particular components (soil, crops, livestock and/or households) of the farm system. Nevertheless, mixed crop-livestock farm systems are complex as they involve interactions and feedbacks between soil, crops, livestock and people. In SSA, studies that quantified through direct observations and analyzed simultaneously nutrient management, livestock feeding and herd management as well as food availability in the household are lacking. In addition, there is no quantitative information on the interactions between farms and their impact on crop and livestock production. For example, to the best of our knowledge, in semi-arid West-Africa, the amount of crop residue remaining on the soil in fields as affected by free grazing has not been quantified, and the same applies for the impact of biomass (grain, crop residue and manure) exchange between farms on their crop and livestock production and food security.

Therefore, we conducted detailed farm monitoring of the cropping system, the livestock system and the household for 13 months in 22 farms belonging to four contrasting farm types in semi-arid Burkina Faso (Assogba et al., 2022). The main objective of our study was to assess the extent to which the current management options were able to sustain crop and livestock production and fulfil household food requirements. The specific objectives were to analyze, per farm type, (1) the nutrient balance and the dynamics of crop residues remaining on the soil at field level, (2) the livestock feeding strategies as well as the feed gap throughout a year, (3) the food availability, inflow and outflow in households throughout a year, and (4) the impact of biomass exchange between farms on their crop and livestock production.

3.2 Materials and methods

3.2.1 Study area

This study was carried out in the semi-arid zone of Burkina Faso. The climate of the region is characterized by one rainy season from June to October followed by a cold dry season from December to February and a hot dry season from March to May. The average annual rainfall is 676 mm; the average minimum and maximum temperature are respectively 17 °C (January) and 39 °C (April). The data collection took place from 2020 to 2021, each year having a total rainfall of 846 mm and 457 mm respectively. The soil texture in the study area is sandy (58%) with 21% of silt and 21% of clay. The organic matter and nitrogen content of the soil were low and respectively equaled 1% and 0.5%. Further details on the physical and chemical parameters of the soil are presented in Figure S2 (Appendix 2). The semi-arid zone of Burkina Faso is dominated by mixed farms combining crop and livestock activities. The study was conducted in the villages of Yilou and Tansin (Figure 3.1). Yilou (13.02°N; 1.55°W) is located in the province of Bam and covers about 35 km^2. The presence of a national road crossing the village offers farmers small commercial opportunities as source of off-farm income. Gold mining is another source of off-farm income. Livestock production is facilitated by the presence of a river (Nakambe) used by animals for drinking. Tansin (12.76°N; 0.99°W) is located in the province of Sanmatenga and covers an area of 4 km^2. As the village has no access to a river, the farmers created an artificial lake to store water during the rainy season for the livestock. Compared to Yilou, Tansin is more isolated, resulting in poorer access to markets.

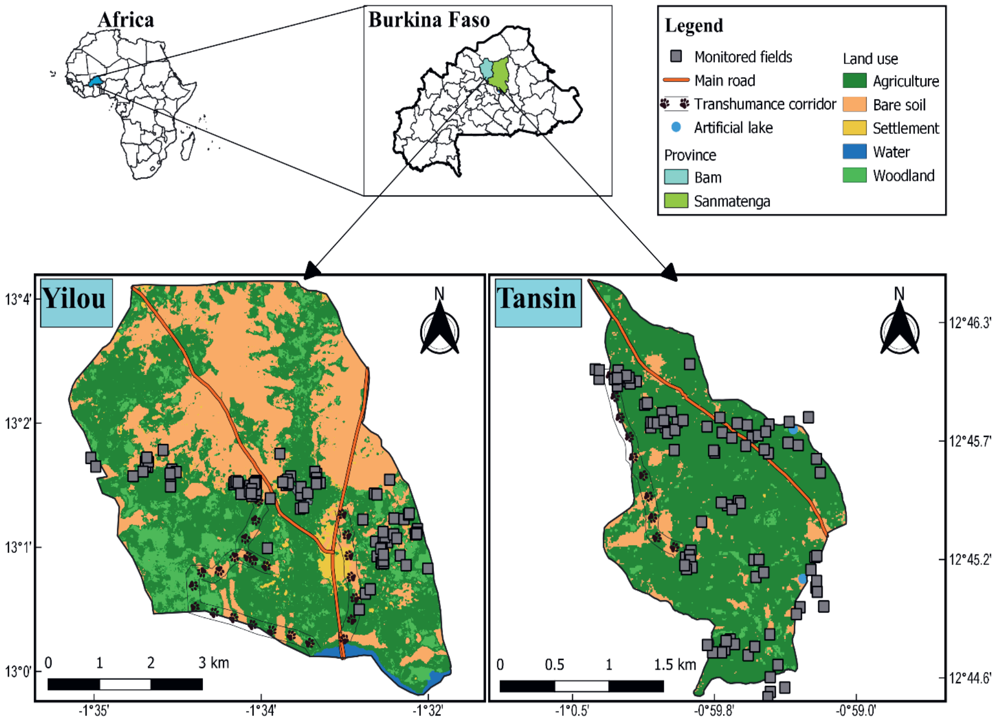


Figure 3.1: Map of the study areas showing land use and monitored fields (87 and 90 fields in Yilou and Tansin respectively)

3.2.2 Farms selection

Biomass management and dynamics were monitored with volunteer farmers representing the diversity of farms in the study area. This diversity was determined using a statistical typology to classify farms according to their resource endowment and production goals (Assogba et al., 2022). Two subsistence farm types differed by their orientation on crops (Subsistence-Oriented Crop – SOC) and small ruminants (Subsistence-Oriented Livestock – SOL). Another farm type (Market-Oriented and Diversified – MOD) had the largest cultivated area, larger herd size and was more involved in cattle fattening than SOC and SOL, with more than half their total revenue coming from off-farm activities. The last type (Land Constrained Livestock – LCL) rented in 50% of its cultivated land and had by far the largest herd size. In order to identify volunteer farms, one workshop was organized in each village to explain and discuss the biomass monitoring work (3.2.3) to be implemented with farmers. Finally, 22 volunteer farms, representing the diversity in the farming system of the study area, were selected (Table 3.1) for the monitoring of biomass production and management.

Table 3.1: Characteristics (mean and standard deviation) of monitored farms. Variables with the same letters are not significantly different.

Farm types	Total cultivated area (ha)	Cultivated area allocated to legumes (%)	Herd size (TLU)	Small ruminant ratio (%)	Family size (Adult equivalent)	N
LCL	2.3±1.3^{a}	4.7±6.5^{b}	31.7±7.9^{a}	13±6.8^{d}	5.2±1.6^{ab}	4
MOD	3.9±2.4^{a}	11.5±11.3^{ab}	5.3±3.5^{b}	37.4±19.2^{b}	7.8±2.5^{a}	7
SOC	2.5±1.2^{a}	18.5±14.9^{ab}	3.5±1.2^{c}	33.4±17.4^{c}	3.9±0.9^{b}	6
SOL	2.7±1.4^{a}	23.5±19.6^{a}	2.2±1.2^{d}	54.8±15.2^{a}	4.4±1.7^{b}	5

TLU = Tropical Livestock Unit. N: number of monitored farms. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock. N: number of farms selected

3.2.3 Biomass monitoring

A quantitative tracking of biomass inflow and outflow at field, cropping system and farm level was carried out from December 2020 to December 2021. Hence, the present study could not capture biomass management strategies linked to inter-annual rainfall variability. In this study, the term biomass encompassed crop residues, grain, manure, livestock and concentrate (cotton seedcake and sorghum bran) fed to livestock. At field and cropping system level, manure applied to field(s) was considered biomass inflow whereas grain and crop residues harvested were considered as outflow. The amount of crop residues remaining on the soil in fields as mulch was also monitored (see 3.2.3.2). At farm level, biomass inflow included biomass imported (e.g. bought or received) by the household, whereas biomass outflow concerned biomass exported (e.g. sold or given away) and livestock death. Besides inflow and outflow, all biomass produced (except manure) within the farm was also monitored. Grain consumption by household members was not recorded, but calculated based on average food needs (see 3.2.4.3). Two Open Data Kit (ODK) forms were developed to collect data on crop residues remaining on fields on the one hand, and biomass management on the farm on the other hand. Two agronomists, trained on the data collection methods, assisted with the data collection in both villages. The timing of the data collection is detailed in sections 3.2.3.1 to 3.2.3.3.

3.2.3.1 Field monitoring

Each field cultivated by the 22 farms was first delimited using a Global Positioning System (GPS). This first step allowed the calculation of the cultivated area per crop by each farm. The amount and timing of input (seeds, fertilizer, manure, herbicide, pesticide) applications in each field were directly recorded as well as the timing of cropping operations (seedling, fertilization, application of herbicide/pesticide, weeding). The fields were cultivated in monoculture or intercropping. Intercropping was mainly done with the traditional intra-hill method, which consists of simultaneously sowing sorghum (*Sorghum bicolor* (L.) Moench) or millet (*Pennisetum glaucum* (L.) R.Br.) and cowpea (*Vigna unguiculata* L. Walp) in the same planting hill. At harvest, the fresh weights of crop grain and residue produced were measured in 5 m x 5 m sampling quadrants. One quadrant was placed in a representative area of each field, including in intercropped fields. In intercropped fields, the same quadrant was used to measure the fresh weights (grain and residue) of each intercropped species at harvest. We also determined the proportion of intercropped species by counting the number of plants of each species and dividing it by the total number of plants in the quadrant. Grain and residue samples (100 g) were then collected and dried (open air) for seven days to obtain the water content and calculate the dry weights. Indeed, due to the distance between the fields and the laboratory, and the number of samples (> 500) collected, all samples were dried open air for seven days. We assumed this approach was enough to remove the water content of the samples, given the hot and dry conditions during the dry season. After the harvest, once farmers collected grains and crop residues from fields, the amount of remaining crop residues on the soil (i.e. not harvested) was weighed within a 5 m x 5 m quadrant in a representative area of the field. In intercropped fields, the proportion of crop residues harvested for each species was assumed homogeneous and was calculated by dividing the total dry matter harvested by the total dry matter produced. In total 177 fields were monitored. The field monitoring activities took place during the 2021 growing season.

3.2.3.2 Variation in crop residues biomass remaining on the soil

The amount of crop residues (dry matter) left on the soil after harvest was measured each week from December 2020 to February 2021 (three months), when no crop residues were left on the soil. For each farm, the most fertile and the least fertile fields of sorghum according to the farmer were monitored to reveal potential differences in mulch management. The assumption was that soil fertility could impact crop residues management, especially the amount of crop residues used as mulch. Data on soil fertility were lacking when the monitoring of crop residues started, but in Burkina Faso, farmers' knowledge of their soil has been demonstrated to be scientifically valid (Gray and Morant, 2003). Soil samples were later collected at 0-15 cm depth in monitored fields at the end of the 2021 growing season to determine their texture and nutrient contents (Figure S2, Appendix 2). The results are analyzed in section 3.3.1. Some farms only had one cultivated field, in which case this field was considered as their most fertile field. Each week, the amount of crop residue biomass remaining on the soil was weighed using a sampling framework (Figure 3.2), made up of five sampling plots of 1 m x 1 m. The central plot location was chosen randomly. The amount of crop residues in each plot was weighed and the average value from the five plots was retained. This approach was replicated three times to capture the spatial heterogeneity of crop residues distribution in the field and the average of the three measurements was retained. The decline in remaining crop residues was attributed to livestock grazing, hence the impacts of decomposition and other potential uses (e.g. cooking) were neglected.

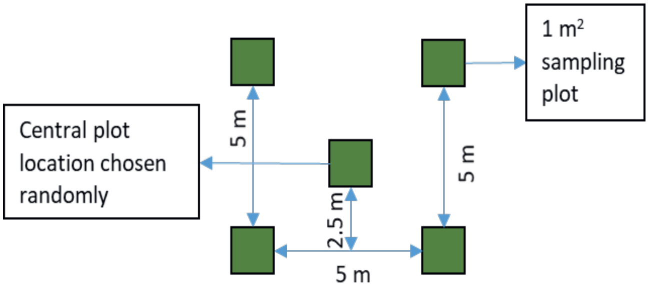


Figure 3.2: Sampling framework used to measure the amount of crop residues remaining on the soil

3.2.3.3 *Monitoring of household biomass management*

Inflows and outflows of crop residues, concentrate and grain, at farm level, were recorded (in kg of dry matter) every week whereas livestock flows were recorded every two weeks. Biomass exchange (kg of dry matter) between households, including exchange of crop residues for manure and vice versa, grain/crop residues/manure given away or received as aid, were also quantified weekly. The amount of biomass exchanged was converted into equivalent of kg of Nitrogen as common basis for comparison between exchange of different nature (e.g. crop residue and manure) (see section 3.2.4.1 for how the conversion was done).

The amounts of crop residues and concentrate fed to livestock were quantified using a form filled out every day by farmers. This form was co-designed with the 22 volunteer farmers (Figure S1, Appendix 2), during one workshop in each village. In addition, each engineer closely followed all farmers to support them in properly filling out the form. The form was filled out using local units defined by farmers during the workshop, including buckets and bundles. For each local unit, the equivalent weight in kilogram of dry matter was obtained by weighing different livestock feeds (crop residues and concentrate) three times in each of three different farms and taking the average. In addition, the herd size and structure, births, inflow (purchases) and outflow (sells and deaths) of animals and products (milk) as well as days spent by livestock outside the farms were recorded every two weeks.

3.2.4 Indicator assessment

To assess the sustainability of current practices for soil, livestock and household, indicators were calculated for each farm investigated. For the soil, nutrient balances and use efficiencies were calculated at field and cropping system level. A positive nutrient balance combined with a nutrient use efficiency between 50% and 100% was considered an indicator of good soil nutrient management. For the livestock, the gap between livestock feed requirement and feed given by farmers was calculated for metabolizable energy and protein at farm scale and per animal. A null or negative gap would imply that farmers were able to sustain their livestock without relying on grazing. The larger the gap, the greater is the dependence of farms on grazing areas. Concerning households, the food gap between the household requirement and production, was calculated on a yearly basis. A food gap equal or less than zero signifies that a given household reached food self-sufficiency.

3.2.4.1 Partial nitrogen balance and nitrogen use efficiency

Nitrogen (N) is one of the major nutrients for adequate crop growth and one of the main limiting nutrients in cereal-based cropping system (Kihara et al., 2016; Ten Berge et al., 2019). Therefore, we focus our analysis of the cropping system sustainability on N balance and N use efficiency. The partial N balance at field and cropping system level was calculated using respectively eq. 1 and eq. 3. The nitrogen use efficiency (NUE) at field and cropping system level was calculated using respectively eq. 2 and eq. 4. N inputs in a field included the addition of N through applied manure, applied mineral fertilizer, and N fixed by legumes, per ha. We assumed a manure N content of 1.3% and 1.5% of dry matter for cattle and small ruminants respectively (Sileshi et al., 2017) and for NPK fertilizer and urea an N content of 23% and 46% was taken respectively. N fixation from the atmosphere by legumes was calculated by taking 64% and 70% of the total yield (crop residues and grain produced per ha) of cowpea (*Vigna unguiculata* L. Walp) and peanut (*Arachis hypogea* L.) respectively (Phoomthaisong et al., 2003; Sanginga, 2003). The same proportion of N fixation from the atmosphere was used for both peanut and Bambara nut (*Vigna subterranea* L. Verdc.). N inputs at cropping system level were calculated as the sum of N applied (manure and fertilizer) and fixed (by legumes) in all fields divided by the total area cultivated.

N outputs at field level involved the sum of amounts of N in grain and crop residues harvested per ha. At cropping system level, N outputs was the sum of amounts of N in all grains and crop residues harvested by a farm, divided by the total area cultivated. The total N content of grains and crop residues were derived from the feedipedia database (www.feedipedia.org, accessed on 01/06/2022).

Field level: $\text{Nbal}_{\text{fl}} = Ninput - Noutput$ (eq. 1)

$$\text{NUE}_{\text{fl}} = \frac{Noutput}{Ninput} \quad \text{(eq. 2)}$$

Cropping system level: $\text{Nbal}_{\text{cs}} = \frac{\sum_{i=1}^{n} A_i\,(Ninput_i - Noutput_i)}{A_T}$ (eq. 3)

$$NUE_{cs} = \frac{\sum_{i=1}^{n} A_i\,(Noutput_i)}{\sum_{i=1}^{n} A_i\,(Ninput_i)} \quad \text{(eq. 4)}$$

Where Ninput and Noutput are respectively the nitrogen input and output from a field in kg/ha. A_i is the area of the ith field (in ha) while A_T is the total cultivated area by the farm (in ha). Nbal_{fl} and Nbal_{cs} are respectively the nitrogen balance at field and cropping system level in kg/ha. NUE_{fl} and NUE_{cs} are respectively nitrogen use efficiency at field and cropping system level in kg/kg.

3.2.4.2 Livestock feed self-sufficiency

The livestock feed requirement was determined using AFRC (1993) equations. Metabolizable energy and protein required for maintenance were calculated using equations 5 – 8. The daily walking distance, which is used to determine the coefficients (0.037 and 0.048 in eq. 5 and eq. 6 resp.) in the metabolizable energy formulas, was assumed to be 11.7 km and 14.4 km (average of rainy and dry season) for cattle and small ruminants (sheep and goats) respectively (Zampaligre and Schlecht, 2018). All other coefficients are default values of AFRC (1993) equations. The metabolizable energy formula for cattle was also used for donkeys.

Metabolizable energy requirement (MJ/day)

Cattle and donkey $\text{ME} = \frac{0.53(W/1.08)^{0.67} + 0.037W}{k_m}$ (eq. 5)

Small ruminants $\text{ME} = \frac{0.315W^{0.75} + 0.048W}{k_m}$ (eq. 6)

$$\text{k}_\text{m} = 0.35\left(ME_f/GE_f\right) + 0.503 \quad \text{(eq. 7)}$$

Metabolizable protein requirement (g/day)

Cattle, donkey and small ruminants $\text{MP} = 2.3W^{0.75}$ (eq. 8)

Where: W is the weight of the animal in kg, which we assumed to be constant throughout the year. We assumed the following: 1 cattle = 0.7 TLU, 1 donkey = 0.5 TLU and 1 small ruminant = 0.1 TLU, where TLU stands for Tropical Livestock Unit and 1 TLU = 250 kg (Le Houerou and Hoste, 1977). ME is the metabolizable energy required for maintenance by the livestock in Mega Joules per day (MJ/day). MP is the metabolizable protein required for maintenance by the livestock in gram per day (g/day). k_m is the efficiency of utilization of metabolizable energy in feed by livestock. ME_f and GE_f are respectively the metabolizable energy and gross energy contents of feed in MJ/kg of dry matter.

ME, gross energy and crude protein content of feed were taken from the feedipedia database (www.feedipedia.org, accessed on 01/06/2022) except for Piliostigma (*Piliostigma reticulatum* DC. Hochst), for which ME and crude protein content were taken from the sub-Saharan Africa feeds composition database (www.feedsdatabase.ilri.org, accessed on 14/06/2022). The crude protein content of feed was transformed into MP following the procedure described in AFRC (1993). The ME and MP content of feed are presented in supplementary materials (Table S1, Appendix 2).

The gap between ME and MP required and directly provided by farmers to livestock was calculated at farm level (eq. 9 and 11) and per TLU (eq. 10 and 12) on a daily basis. This gap is called the on-farm feed gap. We assumed that whenever the amount of feed supplied on-farm was less than the amount required, the gap was obtained through grazing, based on the observation that animals did not starve during our study period (3.3.4). However, the real contribution of pasture to livestock feeding was not measured.

$$\text{FarmGap}_{ME,farm}\ (\%): \frac{100(ME\ required - ME\ supplied)}{ME\ required} \qquad \text{(eq. 9)}$$

$$\text{FarmGap}_{ME,TLU}\ \text{(MJ ME/TLU/day)}: \frac{ME\ required - ME\ supplied}{HerdSize} \qquad \text{(eq. 10)}$$

$$\text{FarmGap}_{MP,farm}\ (\%): \frac{100(MP\ required - MP\ supplied)}{MP\ required} \qquad \text{(eq. 11)}$$

$$\text{FarmGap}_{MP,TLU}\ \text{(g MP/TLU/day)}: \frac{MP\ required - MP\ supplied}{HerdSize} \qquad \text{(eq. 12)}$$

Where ME and MP are respectively in MJ/day and g/day. “HerdSize” is the total livestock present in the farm expressed in TLU.

3.2.4.3 Households food self-sufficiency

The daily energy requirement of adult men and women was set to 2250 kcal per day (FAO et al., 2001). The energy content of food was retrieved through the U.S. Department of Agriculture database (https://fdc.nal.usda.gov/index.html, accessed on 15/06/2022), except for Bambara nut (*Vigna subterranea*), for which the energy content was taken from Mazahib et al. (2013). By first converting the total amount of grain produced by the household into energy, the gap in energy was calculated for a period of one year using eq. 13.

$$\text{HHEnGap}\ (\%): \frac{100(Energy\ required - Energy\ produced)}{Energy\ required} \qquad \text{(eq. 13)}$$

$$\text{Energy required (kcal/year)}: \quad DER\ \text{x}365\text{x}\ AE \qquad \text{(eq. 14)}$$

Where HHEnGap is the household energy gap. DER is the daily energy requirement in kcal/day and AE is the household size in Adult Equivalent, which was calculated following the modified OECD (Organization for Economic Co-operation and Development) scale, giving a value of 1 to the household head, 0.5 to other adults and 0.3 to children (https://www.oecd.org/economy/growth/OECD-Note-EquivalenceScales.pdf). The energy content of food was expressed in kcal/kg. Potential post-harvest loss as well as the potential contribution of livestock products (meat, milk) were not considered.

3.2.4.4 Comparison across farm types

Quantitative comparison across farm types was conducted using a non-parametric analysis of variance (Kruskal-Wallis) (Hollander and Wolfe, 1973) with a 5% threshold. The analysis was followed by a Kruskal-Wallis post hoc test (Conover, 1999) to make groups of similar and/or different means. In addition, linear regression was used to analyze the variation of remaining crop residues biomass left on the soil. Linear correlation was used to analyze the impact of distance between fields and farm settlement on nitrogen balances, respectively. Data analysis was performed in R 3.6.2 (R core team, 2019).

3.3 Results

3.3.1 Nutrient management at field and cropping system level

Nitrogen inputs in fields were generally smaller than the outputs (Figure 3.3A and Figure 3.3B). Indeed SOC, LCL, SOL and MOD farms exported more nitrogen than they provided in respectively 64%, 76%, 85% and 87% of cultivated fields. Only 4% of investigated fields were below 50% NUE implying inefficient use of nitrogen inputs. SOC farms were the first concerned with 9% of their fields (12% of the total cultivated area) with less than 50% NUE. Only few (17%) fields had an acceptable N management i.e. had a NUE between 50% and 100%. SOC farms had the highest proportion (27%) of fields, representing 30% of the total cultivated area, with acceptable N management. On the opposite, only 11% of fields, equivalent to 7% of the total cultivated area had an acceptable N management in MOD farms.

At field level, the N balance was not significantly affected by the cultivated area or the distance from the settlement to the field (Figure 3.3A), irrespective of the farm type and the cropping system (sole or intercropping) (p-value > 0.05 in all cases, tables S3 and S4 in Appendix 2). Similarly, cereal-legume intercropping did not affect the N balance at field level (Figure 3.4A). Whereas a considerable proportion (39%) of cultivated sorghum and millet fields were intercropped with legume crops, such as cowpea and peanut, the proportion of legumes in these fields was small and varied from 1 to 17% with an average of 8%. Moreover, the amounts of N applied as manure and fertilizer in intercropping and sole sorghum and millet fields were similar (resp. 23 kg N/ha and 19 kg N/ha, p-value = 0.6) in general and across farm types (Figure 3.4A). Similar results were observed considering, in addition to N applied by farmers, N fixation from atmosphere by legumes. The only exception were LCL farms which had a higher N inputs in intercropping. N outputs from intercropped fields were greater on average than N outputs in sole cropped fields but the difference was not statistically significant, except for MOD farms. We found no differences across farm types in the N balances of cereals in sole cropping and intercropping. Likewise, no statistical differences were found between the nitrogen inputs, outputs and balance of the sorghum fields perceived to be most and least fertile by farmers even if the average balance was slightly better in the most fertile field (-5 kg N/ha) than in the least fertile field (-7 kg N/ha) (Figure 3.4B). When comparing laboratory results with farmers' perceptions of soil fertility, we found higher pH, calcium, available P and K content in the field of sorghum that was most fertile according to farmers (Figure S2, Appendix 2). However, there was not a clear difference in N content between the most fertile and least fertile field.

At the cropping system level, the nitrogen input per ha was highest for LCL farms followed by SOC, MOD and SOL farms (Figure 3.3C). The contributions of fertilizer, legume and manure to the total nitrogen (N) input at cropping system level were similar across all farm types (Figure 3.3D). The main sources of N input in the cropping system were N fixation by legumes (46%) and N input from manure (41%), whereas N from fertilizer contributed the least (13%) (Figure 3.3D). However, for LCL farms, owning the largest herd, manure was the most important source of N inputs, representing on average 52% of the total amount of N applied to fields. Interestingly, N fixation by legume crops represented a significant share of the N input of all farms, and was especially important for MOD farms (62% of their N inputs). N depletion was larger in LCL and MOD farms followed by SOL farms. Only SOC farms had on average a positive N balance in their cropping system with half (three farms) of them having a negative balance and the other half a positive balance (Table 3.2). However, there was no significant difference in NUE across farm types.

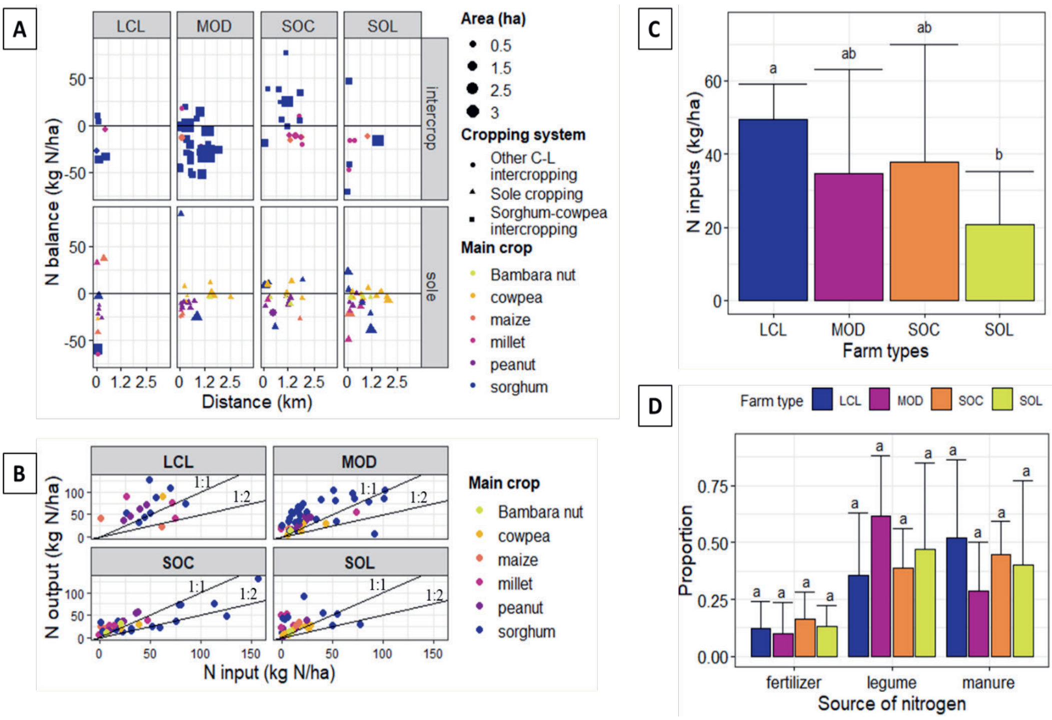


Figure 3.3: (A) Nitrogen balance as function of distance of fields to households' settlement in intercropping and sole cropping. C-L = Cereal-Legume. (B) Field-level N output versus N input, with indication of nutrient mining (fields above the 1:1 line), low nutrient use efficiency (fields below the 1:2 line) and adequate nutrient use efficiency (fields in between lines). (C) Average nitrogen input in the cropping system per farm type. (D) Mean contribution of each source of nitrogen to the nitrogen input of the cropping system of each farm type. Error bars indicate the standard deviation. For each source of nitrogen, bars with the same letter are not statistically different. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

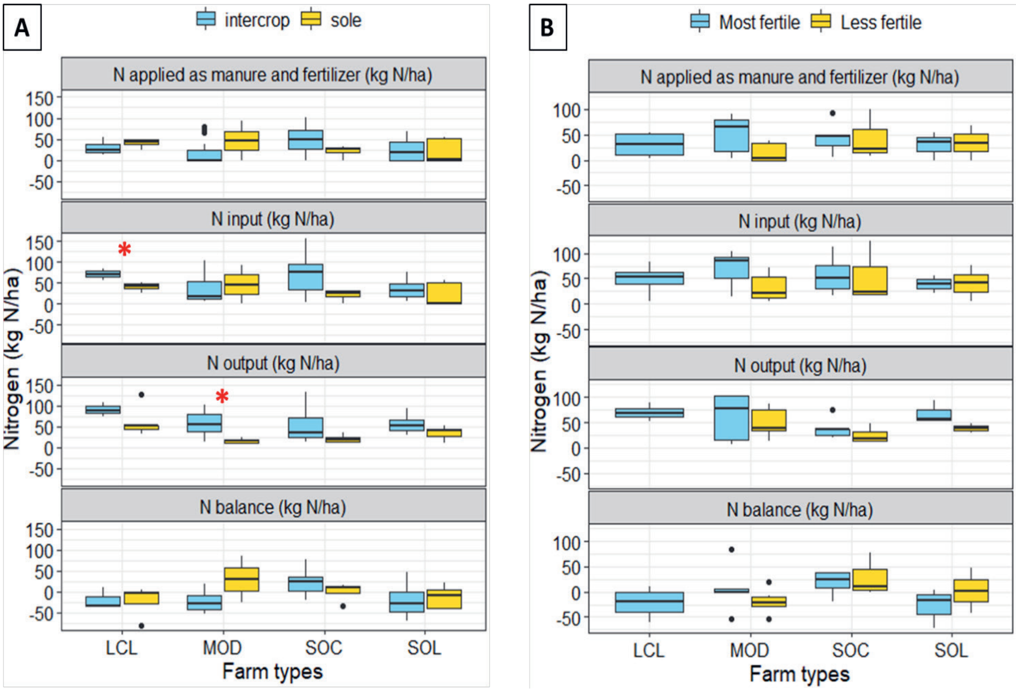


Figure 3.4: (A) Nitrogen applied as manure and fertilizer, input, output and balance in sole cereals and intercropped cereal-legume fields. (B) Nitrogen applied as manure and fertilizer, input, output and balance in the most and least fertile sorghum fields according to farmers. Pairs of boxplots with a red asterisk on top are significantly different (p-value < 0.05). LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

Table 3.2: Mean ± standard deviation of nitrogen use efficiency (cropping system level) and nitrogen balance (at field and cropping system level) per farm type. Variables with the same letter across farm types are not statistically different at 5% threshold.

	Cropping system level	
Farm types	N balance (kg N/ha)	NUE (kg/kg N)
LCL	-25±20b	1±0a
MOD	-19±17b	2±1a
SOC	8±17a	1±0a
SOL	-12±18ab	3±2a

LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

3.3.2 Management of crop residues and variation of crop residues remaining on soil

Sorghum, millet, cowpea and peanut were the common crops grown by all farms investigated, hence they were used for analysis across farm types. The amount of sorghum and peanut residues harvested per ha were not significantly different across farm types (Figure 3.5). However, for millet, LCL farms harvested the highest amount of residues per ha while SOC farms harvested the least. LCL and SOC farms harvested most cowpea residues, followed by MOD and SOL farms. Expressed per unit of livestock, LCL farms harvested the smallest amount of crop residues of all crops. For the other farm types, the range of millet, cowpea and peanut residue harvested per unit of livestock was respectively 35-71 kg/TLU, 39-165kg/TLU and 33-62 kg/TLU. In general MOD farms, which are more involved into cattle fattening than others, harvested a larger amount of crop residues per unit of livestock than the other farm types.

Per ha, LCL farms left more sorghum residues on the soil at harvest followed by SOL, MOD and SOC. Compared to sorghum, less millet residues were left on the soil and the amount left was similar across farm types. No peanut and cowpea residues were left on the soil by all farm types.

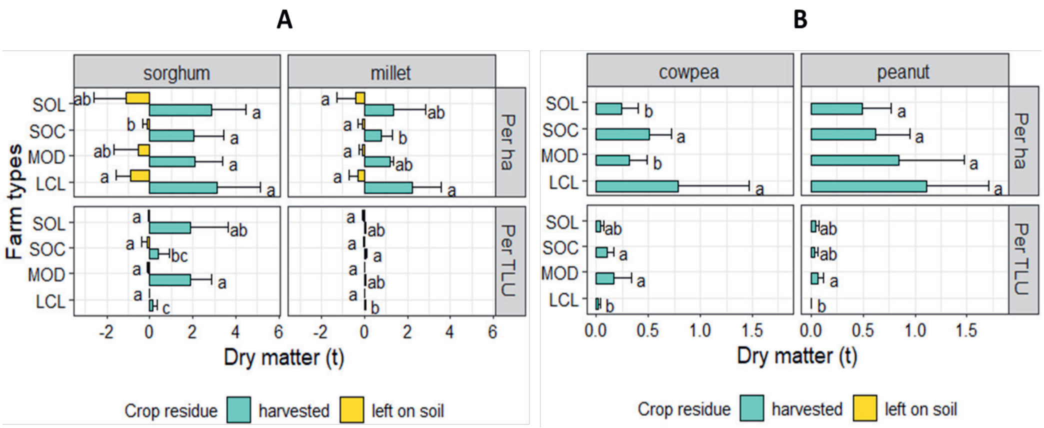


Figure 3.5: mean amount of crop residues harvested and left on soil per ha and tropical livestock unit (TLU) for cereals (A) and legume crops (B). Error bars indicate the standard deviation and bars with the same letter are not statistically different. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

The amount of sorghum residues remaining on the soil at harvest was much larger in the most fertile field than in the least fertile field (Figure 3.6). Except for SOL farms, the amount of remaining crop residues on soil in the least fertile field was almost none. In the most fertile field, on average 739 kg/ha of sorghum residue was left on the soil at harvest, with the MOD type farmers leaving the most and SOL type farmers leaving the least. The weekly decrease in the amount of residues in the most fertile field varied across farm types and was largest for SOL type followed by LCL, SOC and MOD farms. On the least fertile field, the average amount of sorghum residue remaining on the soil at harvest was 386 kg/ha for SOL farms and the weekly decrease in the amount was strongest for the SOL farms as well. After 12 weeks, nothing was left on the fields.

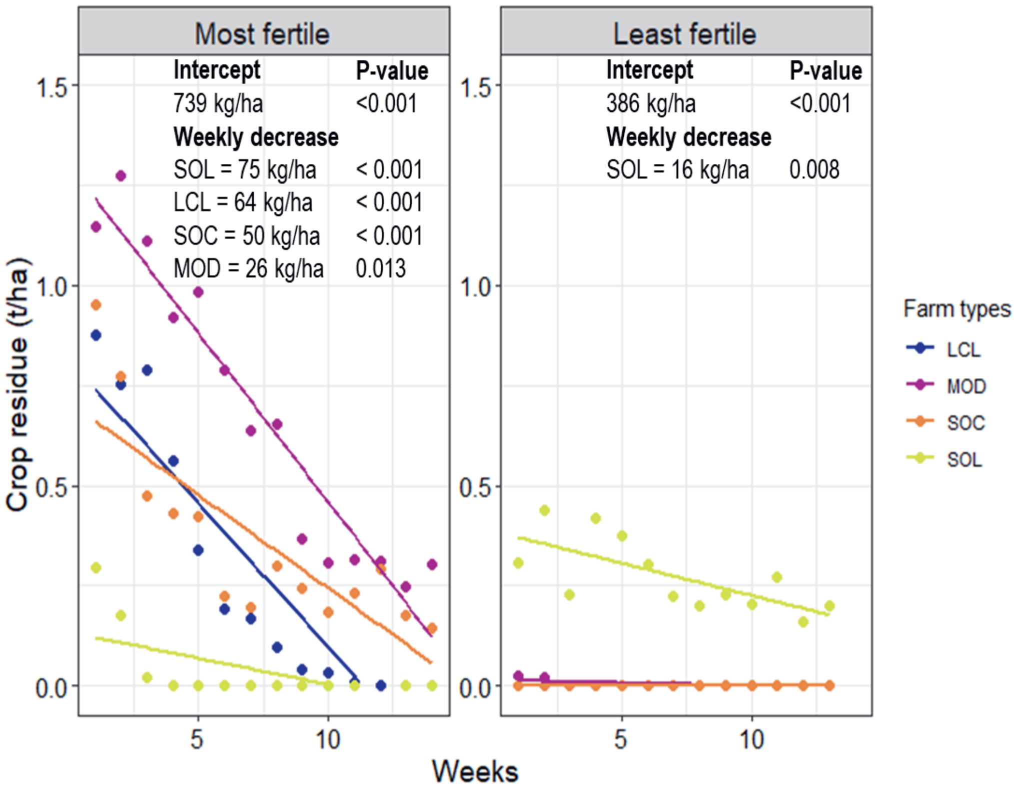


Figure 3.6: Variation of sorghum residue left on soil in the most and least fertile fields. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

3.3.3 Livestock feeding

In all farm types, the amount of feed provided to livestock by the farmers was negligible during the first four weeks after harvest (end of November to end of December) (Figure 3.7). At that time of abundant biomass availability, livestock feed requirements were mostly met through grazing, which is not depicted in Figure 3.7. From the fifth week after harvest, the amount of feed directly provided to livestock increased and reached its maximum in week 20 after harvest, which corresponds to end of April (the hottest month of the dry season). From the beginning of May to the onset of the rainy season (week 30), feed supply by farmers quickly decreased to reach almost none, where it stayed until the next harvest. During the dry season, all farm types purchased on average similar amount of crop residue per TLU to feed their livestock (78 MJ ME/TLU equivalent to 11 kg of sorghum residue per TLU). Likewise, there was no statistical difference (p-value > 0.05) in the average amount of concentrate feed purchased across farm types per TLU. Even if LCL farms, with the largest herd size, purchased the smallest amount (547 MJ ME/TLU equivalent to 49 kg of concentrate feed) while SOC and MOD farms purchased the highest amount (2020 and 1801 MJ ME/TLU resp.).

The maintenance metabolizable energy (ME) requirement of livestock present in the farm was never met through direct feed provided by farmers in all farms except for a few weeks in MOD farms (Figure 3.7A). The average annual feed gap at farm level was significantly different across farm types. Indeed, LCL farms with the largest herd size, had the biggest on-farm feed gap followed by SOC, MOD and SOL farms (Table 3.3). On average across the farm types, at least 73% of the livestock energy requirement was not met through direct feeding and would have been met through grazing given that animals did not starve during our study (3.3.4). Over the whole period of our study, the energy gap per TLU was similar across farm types. The daily gap was on average 41 MJ ME/TLU (6 kg of sorghum residue), so respectively 28.7 MJ ME or 4.1 MJ ME per animal for cattle or small ruminants. This would imply that grazing provided respectively 82% and 61% of the daily energy requirement of a cattle (35 MJ ME) or a small ruminant (6.7 MJ ME). Nevertheless, considering only the dry season, when direct feeding with residues and concentrate is most crucial because of low availability of forage in pasture land, the grazing contribution dropped and represented 51% of livestock maintenance energy requirement as the daily gap amounted to about 28 MJ ME/TLU (4 kg of sorghum residue) on average. The contribution of grazing in the dry season was maximum for LCL farms. On average, for all farms, cereal (sorghum, millet, maize) residues provided most metabolizable energy, followed by legume crop residues (cowpea and peanut) and concentrate feed. In addition, pods of Piliostigma (*Piliostigma reticulatum* (DC.) Hochst.), a native shrub, represented a substantial part (13%) of the biomass fed to livestock. Concentrate feed had a significantly larger contribution in LCL and SOC farms whereas legume residues (cowpea and peanut) had a larger share in SOL and MOD farms.

Similar to the energy requirement, the protein requirement was rarely met through provided feed except for MOD farms (Figure 3.7B). The farm-level feed gap, both for the entire investigated period and the dry season, was significantly larger for LCL farms followed by SOC, SOL and MOD farms (Table 3.3). When considering the entire period, the protein gap per TLU was similar for all farm types whereas in the dry season, it was larger for LCL farms followed by SOC, SOL and MOD farms. On average, 34 % of protein fed to livestock in the dry season came from legume crop residues (cowpea and peanut) while concentrate feed, cereals and Piliostigma pods provided respectively 27%, 21% and 18%. The contributions of the different feed types differed significantly between the farm types. Legume residues contributed the most to protein supply in all farms except LCL farms. Indeed, the contribution of legume residues to livestock protein feeding was lowest for LCL and highest for SOL which also had respectively the lowest and highest ratio of land dedicated to legume cultivation (Table 3.1). The contribution of cereal residues to protein supply was highest in MOD farms and lowest in SOC farms. In LCL farms, the provision of protein through legume residues was likely replaced by concentrate feed.

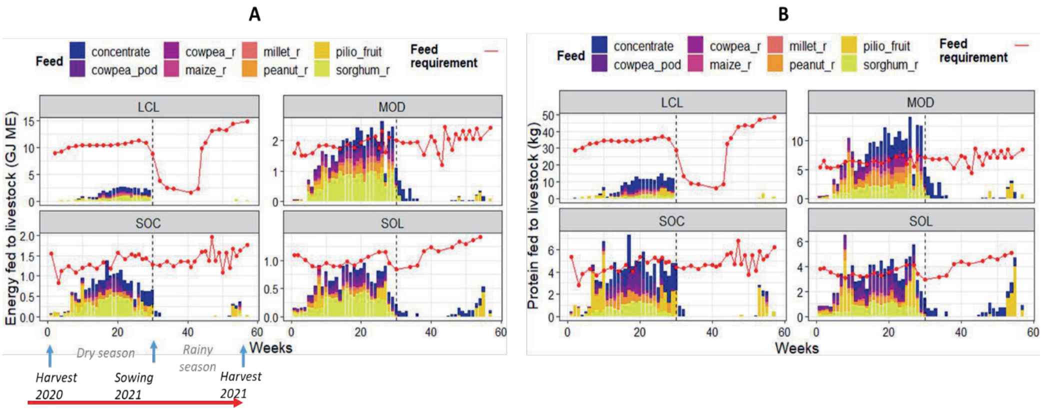


Figure 3.7: Weekly average metabolizable energy (ME) (A) and protein (B) fed to the livestock herd throughout a year per farm type. The red line represent the feed requirement of the herd. Feed names ending with "_r" refer to crop residues, pilio_fruit = Piliostigma pods. The black dotted line is the limit between the dry and the rainy season. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

Table 3.3: Daily mean ± standard deviation of feed gaps and contribution of diverse feed sources to livestock feeding. Feed from grazing is not included.

		$FarmGap_{ME,farm}$ (%)		$FarmGap_{ME,TLU}$ (MJ ME/TLU/day)		Feed contribution (dry season - %)			
		Whole period	Dry season	Whole period	Dry season	Cereals	Legume	Concentrate	Piliostigma
Metabolizable energy	LCL	93±9a	88±10a	50±7a	45±5a	37±19a	11±10c	34±20a	18±31a
	MOD	63±46b	28±44c	36±26a	16±25b	42±16a	34±17a	16±14bc	8±15a
	SOC	76±28b	53±25b	43±16a	30±14b	34±19a	22±14b	24±22b	19 ±27a
	SOL	60±37b	39±31bc	36±22a	24±18b	42±14a	35±10a	14±15c	10±14a
	All	73±36	51±38	41±20	28±20	39±17	26±16	22±20	13±23
		$FarmGap_{MP,farm}$ (%)		$FarmGap_{MP,TLU}$ (g MP/TLU/day)		Feed contribution (dry season - %)			
		Whole period	Dry season	Whole period	Dry season	Cereals	Legume	Concentrate	Piliostigma
Metabolizable protein	LCL	89±14a	81±15a	162±38a	138±25a	21±13ab	15±13c	43±23a	21±34a
	MOD	45±65b	-3±63b	90±129a	-5±123b	24±10a	44±19a	21±16bc	12±19a
	SOC	60±45b	24±40b	116±89a	46±77b	18±13b	29±20b	29±23b	24±32a
	SOL	40±56b	10±51b	85±121a	19±108b	22±10ab	46±14a	17±16c	14±19a
	All	58±53	26±55	111±106	46±106	21±12	34±21	27±22	18±27

ME = Metabolizable Energy, MP = Metabolizable Protein. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock. TLU = Tropical Livestock Unit.

3.3.4 Inflow and outflow of livestock in the farm

Livestock herd management, including the practice of transhumance varied across the study period and farm types (Figure 3.8). LCL farms practiced transhumance starting from the onset of the rainy season until the harvest period (Figure 3.8 and Figure 3.7). In that period, LCL farms sent on average 85% of their livestock in transhumance, southward where vegetation is typically more abundant and livestock can graze on pastures. MOD and SOC farms sent much smaller parts of the herd (respectively 6 and 3 %) out of the farm for grazing during the dry season and the start of the rainy season. However, unlike for LCL farms, their livestock stayed in surrounding villages, under the supervision of a herder. The rest of the rainy season, livestock of all farms (except LCL farms) relied almost exclusively on grazing in pastureland within the village (Figure 3.7 and Figure 3.8). The herds of SOL farms, usually consisting only of small ruminants, were always kept on the farm and grazed within the village.

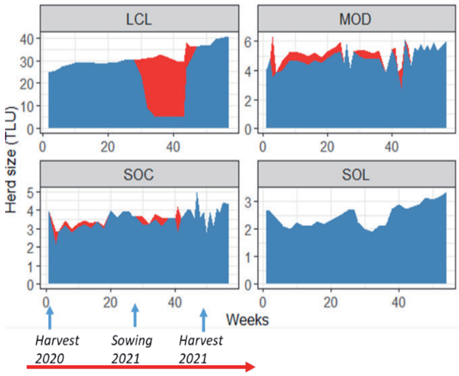


Figure 3.8: herd size, consisting of animals within the village (blue) and out of the village (red) per farm type every two weeks. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

More livestock was sold than bought in all farms (Figure 3.9A). On average, the number of animals sold during the entire study period was not significantly different across farm types and was larger in LCL farms (4.9 TLU) followed by MOD (1 TLU), SOC (0.9 TLU) and SOL farms (0.8 TLU). Livestock was mainly sold in the dry season for all farms except MOD farms. All farm types suffered from similar numbers of dead animals which was negligible and only attributed to diseases, whereas more newborns were recorded in LCL farms followed by the other farm types. However, when taking the herd size into account, the mortality rate was smallest for LCL and SOC (3%) and largest for MOD and SOL (10%). The birth rate was highest for SOL (12%) followed by MOD and SOC (7%) and smallest in LCL farms (5%).

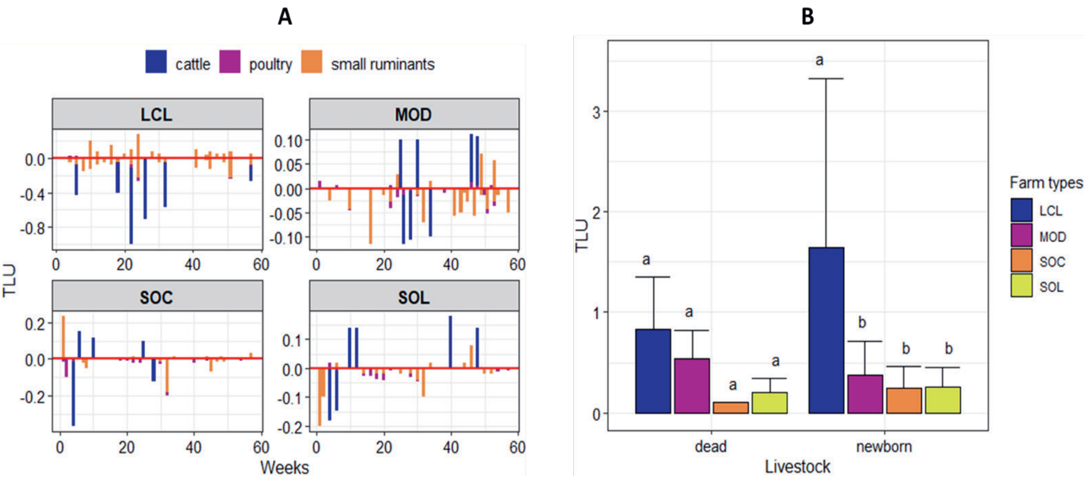


Figure 3.9: Average tropical livestock units sold (negative values) and bought (positive values) by each farm type every two weeks (A). Average tropical livestock units newly born and dead per farm type (B). LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock. TLU = Tropical Livestock Unit.

3.3.5 Food availability in households

The amount of energy produced by households was generally close or greater than their energy requirement (Figure 3.10A), as the household energy gap (HHEnGap) varied on average from -199% (LCL) to -80% (SOC). However, 27% of the monitored farms did not meet their household requirement and two thirds of these farms had a people to land ratio (AE/ha) greater or equal to three.

Farmers of all farm types resorted less to buying grain than to selling (10B). Sorghum was the main crop bought and the amounts purchased over the study period were not significantly different across farm types although SOL and MOD farms bought on average the most (160 and 103 kg/AE resp.) and SOC bought the least (63 kg/AE). Sorghum grain was bought mainly during the lean period i.e. from the end of the dry season to the onset of the rainy season. The total amounts of peanut sold were similar in all farm types with an average of 17 kg/AE. Cowpea was the most frequently sold crop throughout the study period and especially during the rainy season. However, the total amounts sold were small, ranging from 11 kg/AE to 26 kg/AE.

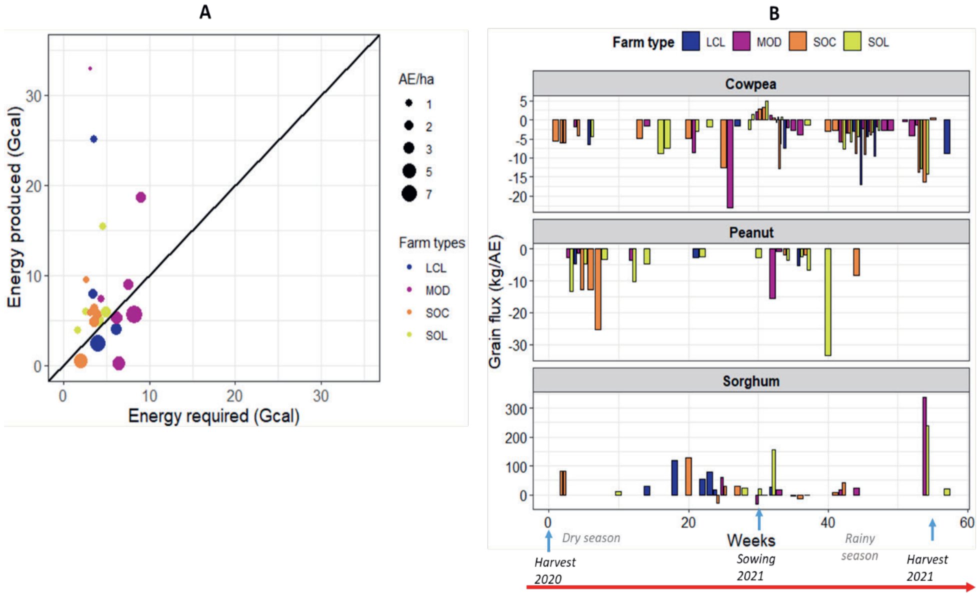


Figure 3.10: Energy produced versus required in 2021 (A). The black line (A) is the first bisector. Weekly Inflow (positive values) and outflow (negative values) of grain in all monitored farms in 2020 and 2021 (B). Gcal = Giga calories. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

3.3.6 Biomass exchange between households

Biomass exchange occurred in all farm types (Figure 3.11A) and revealed solidarity and complementarity between farm types. The main goals of these exchanges included (1) increased food availability for the most vulnerable households, (2) higher application of nutrients to the soil for subsistence farms (SOC and SOL) with limited herd size, and (3) increased feed availability for livestock of big livestock owners (LCL). The most frequent exchange of biomass between farms concerned grain given away and received as aid (48% and 34% resp. of the occurrence of exchanges), sorghum residue given away and received as aid (3% and 5% resp.) and sorghum residue exchange with manure (and vice versa, 6%). In terms of quantity exchanged, grain given away was similar for SOC, SOL and MOD farms (0.3 kg N, equivalent to 17 kg of sorghum grain) but no grain was given away by LCL farms. Likewise, the amount of grain received as aid was not significantly different across farm types and ranged from 0.01 to 0.6 kg N (0.5 to 35 kg of sorghum grain). However, given the small amount in the exchange, grains received as aid would not significantly change food availability in the most vulnerable households (Figure 3.10A). Exchange of sorghum residue with manure occurred only in SOC and SOL farms, which on average sent 0.3 kg N (50 kg) of sorghum residue in exchange of 0.5 and 1.2 kg N (38 and 92 kg) of manure respectively. In addition, only LCL farms exchanged their manure for sorghum residue. They sent on average 1.5 kg N (115 kg) of manure for 1.1 kg N (185 kg) of sorghum residue. However, exchange of sorghum residue with manure (and vice versa) never occurred in MOD farms. The amount of manure received through exchange represented on average 3 and 14% of applied manure of SOC and SOL farms respectively whereas LCL farms sent away the equivalent of only 6% of applied manure. Exchange of sorghum residue for manure therefore played a modest role in closing the nitrogen cycle in the cropping system of SOC and SOL farms which had the smallest herd size and the lowest nitrogen depletion (Table 3.2).

Sorghum residue exchange for manure (and vice versa) occurred only at the end of the dry season (Figure 3.11B). This exchange provided additional manure to farms with limited livestock and fodder to large livestock owners who are strongly constrained by feed availability. Contrary to sorghum and manure exchange, the exchange of grain to support the most vulnerable households occurred throughout the year and mainly during the dry season.

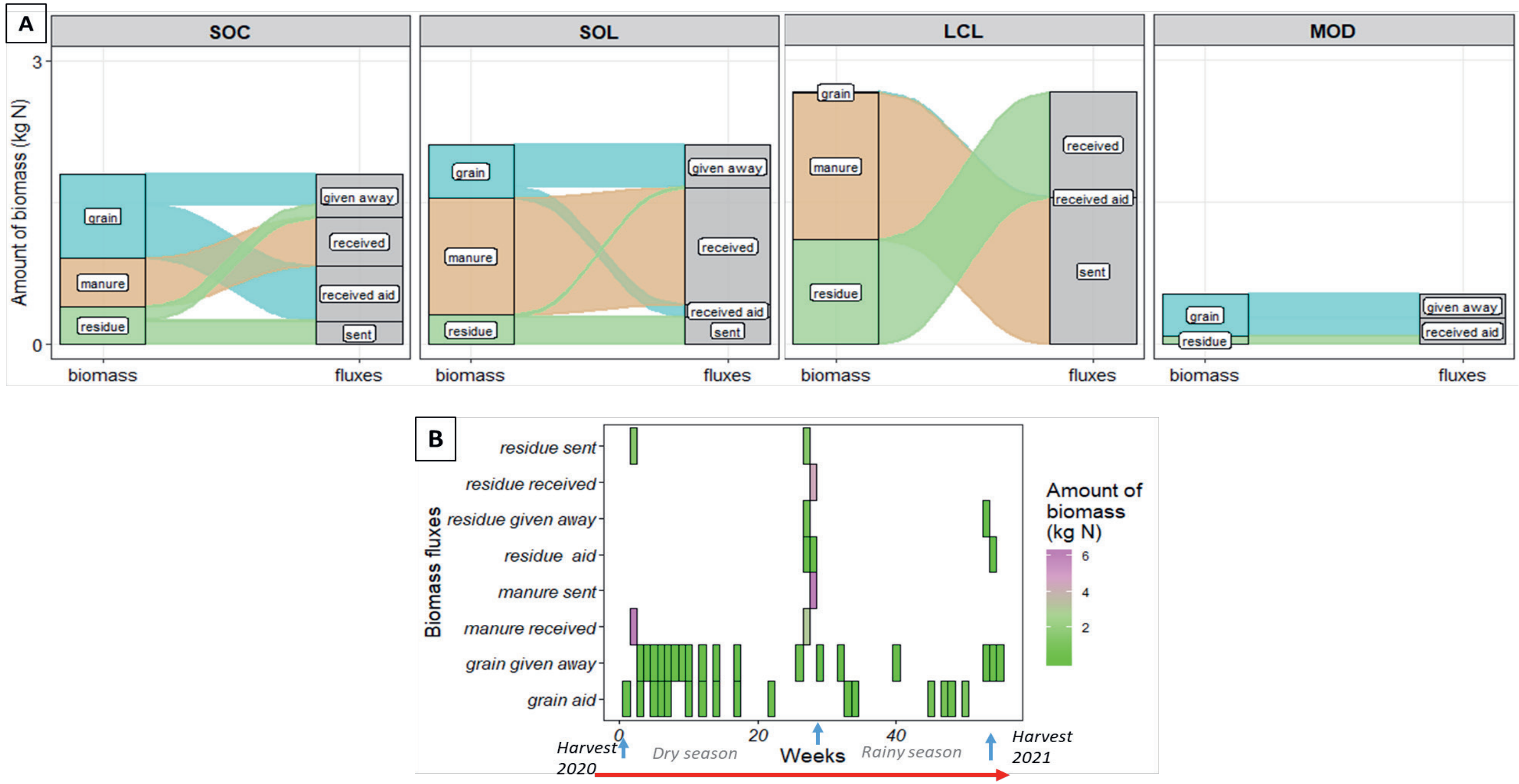


Figure 3.11: (A) Average biomass exchange, expressed in kg of N per farm type over the whole period of study. (B) Weekly variation of biomass exchange between households. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

3.4 Discussion

Crop and livestock production in mixed crop-livestock systems in semi-arid Burkina Faso remains limited (Henderson et al., 2016b). In this study we demonstrated inadequate soil fertility management leading to poor crop production for livestock and households. Poor crop residue production resulted in farmers relying on external feed, mainly from grazing areas, for their livestock. Most households were food self-sufficient except those with higher people to land ratio. Biomass exchange between farms did not have a considerable effect on the farm performance. In the following sections we discuss the impact of current farm management on three components of the farming systems: soil (and crops), livestock and household. Based on these insights and literature, locally-suited options to move toward more sustainable crop and livestock production are discussed.

3.4.1 Can farmers feed their soil?

In general, N inputs (including legume fixation) for most fields were lower than 50 kg N/ha (Figure 3.3B) which is below the national recommendation (78.5 kg N/ha) (INERA, 2022) in semi-arid Burkina Faso, for the fertilization of sorghum, the main cultivated crop. Therefore, reaching N input recommendations would require increased access and affordability of mineral fertilizer as the availability of organic inputs (manure, crop residues) is actually limited. The addition of mineral fertilizer to organic inputs is known to increase crop productivity and potentially lower nutrient loss in the cropping system (Gram et al., 2020). However, at present in Burkina Faso, mineral fertilizer application rate is very low (4.2 kg N/ha) (FAOSTAT, 2022). Similarly, we found an average mineral fertilizer application rates of only 4.6 kg N/ha in semi-arid Burkina Faso. As a result of poor soil fertility management, soil fertility mining has been reported in several studies in sub-Saharan Africa (Cobo et al., 2010; Krogh, 1997; Stoorvogel et al., 1993; Zougmoré et al., 2004b). This study also demonstrated higher nitrogen outputs than inputs at the cropping system level, which indicates a risk of soil mining and declining crop productivity (Adams et al., 2016).

The most important source of nitrogen in the cropping system was N fixation through growing legumes. The integration of N fixing legumes in mixed crop-livestock systems has many advantages, including improved nitrogen availability for other crops such as cereals, better fodder quantity and quality for livestock and reduced pest pressure on cereals (Alvey et al., 2001; Hassen et al., 2017). Reported benefits from N fixing legumes in the cropping system are mainly observed in rotation (sole cropping) (Alvey et al., 2001; Bationo and Ntare, 2000; Franke et al., 2018) or in intercropping with cereals (Falconnier et al., 2016; Sanou et al., 2016; Zougmore et al., 2000). The share of land allocated to the cultivation of sole legume was not negligible in most farms but remained largely inferior to the area dedicated to cereals. Therefore, there is room for legume intensification through the integration of appropriate legume crops and varieties in rotations and intercropping. Indeed, Falconnier et al. (2017) demonstrated the possibility of increased yields and income in Mali through increased integration of cowpea and soybean in sole cropping and intercropping. In our study we showed that traditional intercropping with low proportion (8%) of legumes did not significantly impact the nitrogen balance compared to sole cereal cropping. This suggests that cropping systems in semi-arid Burkina Faso could benefit from increased integration of legumes in cereal-legume intercropping. Indeed, a higher proportion of these legumes in intercropping is beneficial in terms of land equivalent ratio and overall grain and residue production (Bado et al., 2022; Falconnier et al., 2016; Sanou et al., 2016). However, these studies generally refer to strip intercropping which is more labor-intensive in terms of sowing and harvesting, than the traditional, intra-hill intercropping practiced by the farmers in our study (Kermah et al., 2017; Rusinamhodzi et al., 2012). Additional labor requirements in a context of limited mechanization limits the adoption potential of intercropping with higher legume proportion (Ganeme et al., 2021).

Manure was the second most important source of nitrogen in the cropping system. Farmers managed manure in two main ways, consisting of the storage of animal dung, feed refusal and households waste in open-air pits on the one hand and accumulating animal dung and feed refusal in open-air heaps on the other hand. The collected manure was applied to fields at the onset of the rainy season. These types of manure management result in important (more than 50%) dry matter and N loss through N volatilization and leaching (Rufino et al., 2007). Such losses can be avoided with improved practices including roofing, covering manure heap with polyethylene film and reducing the soil permeability where manure is stored. In addition, the amount of manure produced by farms, especially subsistence farms with limited livestock production, is usually not sufficient, explaining massive importation from pastureland areas where animals are parked (Assogba et al., 2022). To lessen the manure shortage, subsistence farms with lower demand for crop residues, sometimes exchanged crop residues to obtain additional manure but the possibility of exchange as well as its effect on N input in the cropping system remained limited given the overall scarcity of biomass.

Another source of organic N inputs in the soil is crop residues mulch. Indeed, the potential benefits of mulch especially in terms of carbon and N inputs and moisture conservation, leading to better biomass production, have been documented (Corbeels et al., 2015). However, as soon as a few weeks after harvest, almost no crop residues were remaining as mulch, because of livestock grazing (Figure 3.5). The management of crop residues at harvest differed per crop and across farm types (Assogba et al., 2022). In fact, only cereal residues were left on the soil after harvest and considered as common resource in the village. Legume residues which represent an important source of protein for livestock were completely harvested as livestock feed, illustrating the high value given by farmers to legume feed as forage (Valbuena et al., 2012). In mixed crop-livestock systems with a context of crop residues scarcity, farmers' preference for livestock feeding over mulch indicates the importance of short-term economic gains from livestock production (Rusinamhodzi et al., 2015) over longer-term gains from soil fertility maintenance. In addition, the recycling of crop residues (and grass) into manure played a significant role in limiting soil nutrient mining as manure represented on average 41% of N inputs.

3.4.2 Can farmers feed their livestock?

Livestock are an important component of mixed crop-livestock farms. Indeed, livestock provide labor, meat and milk, manure and cash and contribute to the social status of farmers in West-Africa (Molina-Flores et al., 2020). In semi-arid Burkina Faso livestock feed on crop residues left on the soil (in fields) as a common resource in the village, crop residues stored at home, purchased concentrate feed (e.g.: cotton seedcake) and forage available in pasture land. Seasonal migration to more humid zones is still a common practice, mostly for farms with big livestock herds (Turner et al., 2014). The strong reliance on free grazing reduces animals' performance in terms of growth and reproduction given the amount of energy required to find adequate forage and the poor quality of forage often available in grazing lands (Fust and Schlecht, 2018). In addition, the considerable gap between livestock feed requirements and availability suggests that the current cropping system is unable to effectively support livestock production. Livestock in semi-arid West-Africa can adapt to the lack of feed by lowering their dry matter intake and their body weight without putting their life at stake (Assouma et al., 2018; Ickowicz and Moulin, 2022). However, the inefficiencies associated with weight fluctuations result in livestock keeping being an extensive activity rather than an intensive one. An alternative for farmers to cope with feed scarcity could be to keep less but more productive animals (Descheemaeker et al., 2016) i.e. adjusting the herd size to the feed production capacity of the cropping system. However, farmers do not only keep livestock for production but livestock can also reflect their social status and represent a capital to cope with hazards and financial uncertainties (Moll, 2005). In all cases, an improvement in the quantity and quality of forage is needed to improve livestock production and reduce farmers' reliance on grazing land in a context of agricultural expansion (Yonaba et al., 2021). Increasing crop residues production for the livestock requires adequate field management practices including the appropriate choice of crops (and varieties) as well as adequate water, nutrients, pest and diseases management (Descheemaeker et al., 2010; Paul et al., 2020). For the semi-arid regions of Burkina Faso, Zampaligré et al. (2022) recommended the use of dual-purpose cereals to feed both humans and livestock. Similar to dual-purpose cereals, dual-purpose legumes have the potential to help close the protein feed gap while still providing a reasonable amount of grain for households. The inclusion of legume forages in the livestock diet contributes to improve the poor quality cereals feed often given to the livestock. For example, Singh et al. (2003) demonstrated the usefulness of dual-purpose cowpea as supplement in livestock feeding through better haulm production compared to local varieties and superior livestock weight gain compared to a sole cereal diet. Moreover, several studies in sub-Saharan Africa demonstrated that the addition of legume forage to cereal crop residues resulted in increased livestock performance (Ajayi, 2011; Ojo et al., 2019). As such, besides improving soil nutrient balances (see section 3.4.1), cereal-legume rotation and intercropping can increase crop residues quantity and quality (Hassen et al., 2017; Matusso et al., 2014). As a supplement to annual crops, the importance of *P. reticulatum* as a source of high-protein fodder was also noted in our study. Dindané-Ouédraogo et al. (2021) and Zubair et al. (2019) demonstrated the utility of Piliostigma pods in livestock feeding. Another strategy to increase feed quality is the integration of forage grasses and trees in the cropping system. For example, the leaves of *Sesbania sesban* (L.) Merr as supplementary protein increased milk and growth rates of lambs in Ethiopia (Mekoya et al., 2009). The use of *Brachiaria brizantha* cv. Piatá resulted in higher milk production of cows in Rwanda (Mutimura et al., 2018). However, these crops are not yet part of the cropping system in West Africa, especially Burkina Faso and therefore their potential integration and benefits requires additional investigation at local level. In Burkina Faso, forage species such as *Eleusine coracana* Gaertn and *Lablab purpereus* (L.) Sweet were introduced but are still not adopted by farmers mainly because of seed price and availability constraints as well as limited land availability (Amole et al., 2022). Another important entry point for improving livestock feeding is the conservation of the forage produced and/or harvested (Balehegn et al., 2021). Indeed, crop residues harvested for livestock feeding is often stored on top of roofs for months during the dry season. These conditions contribute to the degradation of the already poor feed quality (Akakpo et al., 2020; Antwi et al., 2010). The shed system as well as ensilage of forage or storage in polyethylene sacks (in rooms) are proposed as alternatives to the roof storage system to reduce nutrients loss in time but are still not widely adopted mainly because of farmers' limited financial resources (Akakpo et al., 2020; Antwi et al., 2010; Balehegn et al., 2021).

3.4.3 Can farmers feed their households?

Most investigated farms produced enough food to meet their households' requirements and the most vulnerable households can count on solidarity from others. However, despite the solidarity system, 27% of the investigated farms still did not reach food self-sufficiency. A similar proportion was found by Fraval et al. (2020) when investigating food security in semi-arid Burkina Faso. The present study highlighted the importance of the people to land ratio, in reaching (or not) food self-sufficiency. Similar results were found by Falconnier et al. (2015) in Mali and by Giller et al. (2021) in SSA in general. In fact, while a larger household can provide more labor, it can also be a constraint if the cultivated area does not allow sufficient food production to meet the household requirement.

Looking towards the future, Rigolot et al. (2017a) demonstrated that food security in semi-arid Burkina Faso can be achieved through higher inputs of nutrients in the cropping systems while improving livestock feeding in terms of quantity and quality. Moreover, van Ittersum et al. (2016) indicated that yield gap closure combined with sustainable development of irrigation will be needed to feed the population in SSA given its rapid demographic growth. However, factors such as limited wealth, land pressure, labor availability and risk related to rainfall variability prevent them from adopting sustainable options for increased food production. Therefore, income diversification could possibly contribute to food security. The importance of off-farm revenue as a means to alleviate food insecurity was shown by Tankari (2020) and Wossen and Berger (2015) in Burkina Faso and Ghana, respectively. Indeed, off-farm revenue represents extra money that farmers can reinvest in inputs for improved crop and livestock production. It can also possibly be used to purchase additional food (Fraval et al., 2020) to feed the family especially in case of crop failure. Moreover, as shown by Giller (2020), reaching food security in SSA is a complex problem which requires, in addition to sustainable intensification options, appropriate policy interventions. These interventions include (but are not limited to) alternative employment in rural and urban areas to encourage households with non-viable farms to step out, limitation of land fragmentation to counterbalance the diminution of cultivated areas, technical and financial support to farmers (Falconnier et al., 2018; Giller, 2020).

Overall we quantified biomass and nutrient flows for all farm system components as well as biomass exchange between farms, taking into account the farm diversity in our study area. This allowed us to analyze the impact of current management of each system component and their interactions on crop and livestock production. The data collected in this study can be used to build and/or further improve models to explore tailored options for better crop and livestock production at field, farm and village scale. The analysis in this study can be further improved by collecting data on all components of farms for a longer period than one year in order to better understand farmers' management in relation to rainfall variability. Indeed, farmers in semi-arid West Africa can change their management practices in response to the inter-annual variability of rainfall in terms of distribution and total amount (Huet et al., 2020). Therefore, the present study only shows a snapshot of the farm system management. However, monitoring biomass in the whole farm every (two) weeks is very demanding in terms of labor and financial resources, not to mention farmers' willingness to participate in such monitoring. These constraints can limit the feasibility of long-term farm monitoring in the study area.

3.5 Conclusion

Mixed farming systems combine interacting components, including the soil, crops and livestock managed by households. Therefore, changes in one or several of these components will affect other components and the overall farming system. We found that more nutrients were exported than applied in the cropping system under the local conditions of the study region. Grain legumes played a significant role in alleviating the negative nutrient balances at cropping system level but could not completely offset nutrient losses. Overall, the produced crop residues were mainly fed to livestock and recycled into the cropping system in the form of manure. The amount of crop residues harvested was insufficient to sustain livestock production throughout the year. Therefore free grazing in and outside the study villages was essential to meet livestock feed requirements. The cropping system provided enough food for most farms, but households' food self-sufficiency was at risk when three or more adult equivalents had to be fed from one hectare of land. The negative partial nitrogen balance in the inherently infertile soils compromised a sustained crop production, with further repercussions for livestock production and food security of farmers. Moreover, our study confirmed the existence of direct biomass exchange between farms at village scale reflecting complementary and solidarity between farms. However, given the context of biomass scarcity, the potential of biomass exchange to improve crop and livestock production remained limited.

Options to address the gaps and inefficiencies at field, cropping system and farm level can be categorized as (1) integrated soil fertility management, combining increased application of mineral fertilizer with organic amendments (animal manure, mulch), (2) diversification with legumes, (3) good animal husbandry, including keeping less but more productive animals, and (4) better manure management. However, the choice of options to feed the soil, livestock and people will depend on the livelihoods, assets and production goals of farms at short and long term. Further studies should explore, with diverse farmers, the most suitable and affordable options.

3.6 Acknowledgements

We first thank the 22 volunteer farmers who accepted to collaborate with us on the farm monitoring work and who dedicated their time to help us collect data on their farming system. Special thanks to Nock Ouedraogo, Souleymane Sawadogo and Touwende Sawodogo without who the data collection would not have been done in so many farms at the same time. We also thank AMSP (Association Minim Song Panga) for providing us logistics and human resources that greatly facilitate our data collection. Thanks to McKnight foundation for funding this research. Thanks also to the CUOMO foundation for their financial support through their scholarship.

4 QUEEN: a serious game to explore mixed crop-livestock systems in semi-arid Burkina Faso

Abstract

Serious games are seeing as powerful tools to create knowledge and for stimulating (social) learning among participants. The development and use of serious games continues to increase also in the domain of agriculture and natural resource management. However, games based on or suitable for mixed crop-livestock farming system in sub-Saharan Africa (SSA) are still largely lacking. In this study, we developed a serious game (QUEEN) to better understand farmers' decision-making and to explore potential options to improve crop-livestock integration and production as seen from the farmer perspective in SSA using a case study of Burkina Faso. The development of the serious game was an iterative process including farmers and local researchers. The game included options for soil fertility management, crop and livestock production, market opportunities and exchange of information and resources among participants. The objective of each participant in the game was to manage their farm and increase farm-level crop and livestock production and income as much as possible. Three game sessions were organized to collect data on farmers' decision-making and management strategies. Participants represented the diversity of farm systems in the study area and were assigned resources according to the farm type they belonged to. A post-game questionnaire was used to capture information on the degree of realism of the game as well as participants' decisions in the game. The range of possible outcomes of QUEEN was explored with a computer version of the game in which automated participants made random decisions in 30000 simulations. The results of the game sessions indicated that participants' goals in the game differed from the generic goal of the game. Consequently participants' decision-making varied and was not related to their farm type. While the participants remained generally close to their real-life farm management, in the game all applied mulch, strip cereal-legume intercropping and rotations, which is less common in reality, which demonstrates the capacity of the game to encourage farmer to test alternative practices. Participants' outcomes were close to the theoretical optimal outcomes of high cash income and crop and livestock production. However, participants' strategies in the game remained more realistic than those leading to theoretical optimal outcomes. We concluded that the game, complemented by the solution space exploration and the post-game questionnaire, is useful in exploring options for improvement of crop-livestock integration at farm and village scale.

Keywords: serious game, solution space, decision-making, legumes, farm system, sub-Saharan Africa.

4.1 Introduction

Mixed crop-livestock farming systems in semi-arid West-Africa are rather in a vicious cycle than a virtuous one (Henderson et al., 2016a). The productivity of the cropping system and the livestock system remains far from optimal largely due to low input use (mainly nutrients and labor). Also, the synergistic opportunities offered through the recycling of nutrients are still underexploited. As a result, the reliance of the farming systems on external inputs (e.g. fodder and grain) to at least meet livestock feed and human food requirements remains high (Assogba et al., 2023).

One of the main challenges faced by researchers in sub-Saharan Africa (SSA) is to find options that are easily adoptable by farmers (Ronner et al., 2021). In order to ensure that options proposed by researchers fit farmers' needs and capacity, participatory research including farmers from conception to evaluation of actions is now widely used (Descheemaeker et al., 2019). The objective of the participatory approach is to reflect with farmers on options to address jointly identified problems.

A way to stimulate farmers and researchers to actively discuss their understanding of the farming system and proposed options is the use of serious games. Indeed, games are boundary objects that can help reflect on complex systems (van Noordwijk et al., 2020). As a stylized representation of reality, serious games can be seen as models (Valkering et al., 2009) that can be helpful for fostering discussion between farmers and researchers and co-creating knowledge useful for both of them (Delima et al., 2021). In serious games, scientific knowledge is converted into rules that help illustrate the processes leading to the current system state. By serving as a support for learning and discussing, serious games offer the opportunity to explore and design solutions to issues identified by multiple stakeholders. Games can be used to explore the potential effects of these solutions on the components of the farming system (Andreotti et al., 2020; Ryschawy et al., 2022).

Some serious games have been developed in SSA on various subjects, such as agriculture (Pfeifer et al., 2021), land use (Michalscheck et al., 2020), and water management (Mossoux et al., 2016). However, game development and use in research in SSA remain limited (Flood et al., 2018). Moreover, to the best of our knowledge, there is no serious game developed and applied in semi-arid West-Africa that offers a holistic representation of mixed crop-livestock farms. Furthermore, game exploration (Sari et al., 2024) allowing to better understand outcomes probabilities and discuss them with participants does not currently receive enough attention from researchers.

In this paper, we developed a serious game with the purpose of better understanding farmers' decision-making and exploring options for stronger crop-livestock integration and better production of each sub-system (crop and livestock). The objectives of the game were (1) to have a better understanding of farmers' decision-making regarding their resources (land, livestock, crop, money) in the game sessions, (2) to facilitate communication among farmers, and among farmers and researchers, (3) to serve as a virtual laboratory for farmers and researchers to explore the effects of soil fertility, crop or livestock management options at farm scale and (4) to have a better understanding of the farming system functioning, determine limits and opportunities for improvement. The objective of each participant in the game was to manage their farm and increase farm-level crop and livestock production and income as much as possible. The game integrates biophysical, economic and social dimensions of the farming system. We analyzed the degree of realism of the game and participants' choices in the game using a post-game questionnaire. Moreover, the solution space (all the possible outcomes) of the game was explored with computer simulations and farmers' outcomes were analyzed in comparison to theoretical optimal game outcomes.

4.2 Materials and methods

4.2.1 Study area

The serious game entitled QualitativE Evaluator of farm productioN (QUEEN) was developed and applied in semi-arid Burkina Faso, in two villages: Yilou and Tansin. Yilou and Tansin are located in the provinces of Bam and Sanmatenga respectively. The local language spoken is Mooré. The climate in the study area is characterized by one rainy season (June-October) and one dry season (November-May). The average annual rainfall is 676 mm, the average maximum temperature is 39 ºC in April and the average minimum temperature is 18 ºC in January. The farming system is dominated by mixed crop-livestock farms. The main cultivated crops are sorghum, millet, cowpea, peanut and sesame. Four farm types have been identified in the study area (Assogba et al., 2022) and included subsistence-oriented crop (SOC), subsistence-oriented livestock (SOL), market-oriented and diversified (MOD) and land constrained and livestock (LCL) farms. SOC and SOL farms were the dominant farm type and had the smallest family size and revenue and differed mainly in the intensity of crop and livestock production. MOD farms had a bigger herd size than SOC and SOL as well as the highest revenue with more than half of its revenue coming from off-farm activities. LCL farms, only present in Yilou, had by far the largest herd size dominated by cattle. They cultivated the smallest area and relied mainly on grazing on rangelands in the village and transhumance (migration southward to get more abundant forage) to meet their livestock feed requirements.

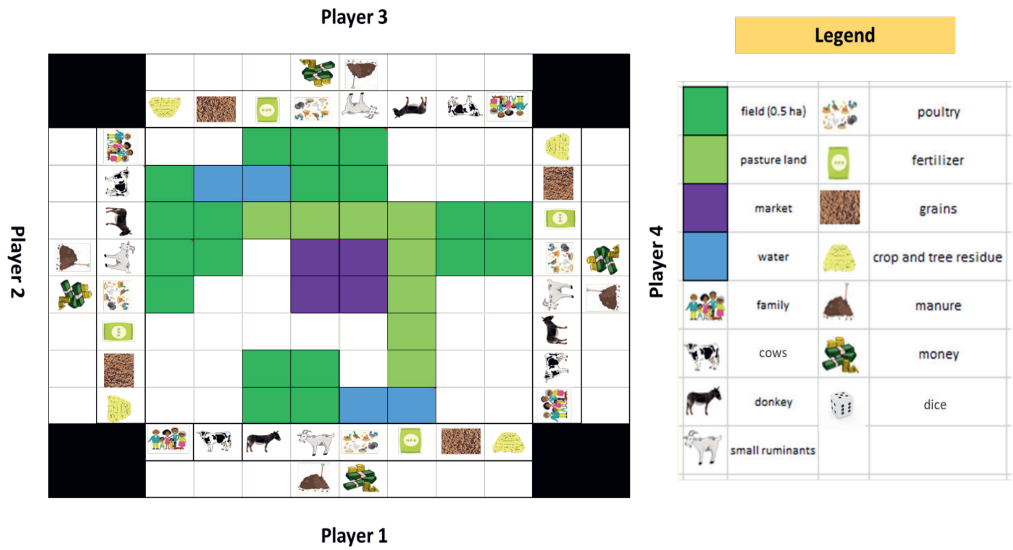
The present study was part of the 3F (Feed the soil and Feed the cow to Feed the people) project which was implemented in Yilou and Tansin. Part of the project consisted in diversification of the sorghum-based system, using legumes in sole cropping, strip intercropping and rotation. The diversification options introduced by the 3F project were included in the game. The farmers who participated in game development and testing as well as game sessions were previously involved for three years in village demonstration trials on strip intercropping of sorghum with cowpea and mungbean as well as sorghum-cowpea/mungbean rotation. Mungbean is not commonly grown in the study area but has been recently introduced and used in on-farm participatory trials.

4.2.2 Game development

The development of the serious game QUEEN (Figure 4.1) started with the ARDI (Actors, Resources, Dynamics and Interactions) approach (Etienne et al., 2011) to identify the components of a social-ecological system (here the farming system) and the interactions between the components (here the farms) through time (4.2.2.4). The results from the ARDI method were combined with knowledge of the biophysical relations of the farm system (Assogba et al., 2023; Assogba et al., 2022) to develop the mechanics of the

2.2.2).

(a)



(b)

Figure 4.1: Board layout of the serious game QUEEN (QualitativE Evaluator of farm productioN) (a). Photo of a game session showing players and the game board (GB) (b).

4.2.2.1 Game development and testing

The development and testing of QUEEN was an iterative process involving researchers and farmers (Figure 4.2). Following identifications of actors, resources, dynamics and interactions to be included in the game, a first version of the game was developed. That version of QUEEN was evaluated by ten researchers familiar with the farming system in several test sessions of the game. The objectives of the test sessions with researchers were to assess the ease to play the game as well as its adequacy with regards to the research questions. Based on these first test, the game was adjusted before playing it with eight volunteer farmers (four in each village). After the game sessions with farmers, they were asked to provide feedback on the ease to play and the realism of the game as well as advice on how to improve it. Based on famers' feedback, the game was again updated before testing it again with researchers. The whole adjustment process leading up to the final version lasted nine months (Table 4.1).

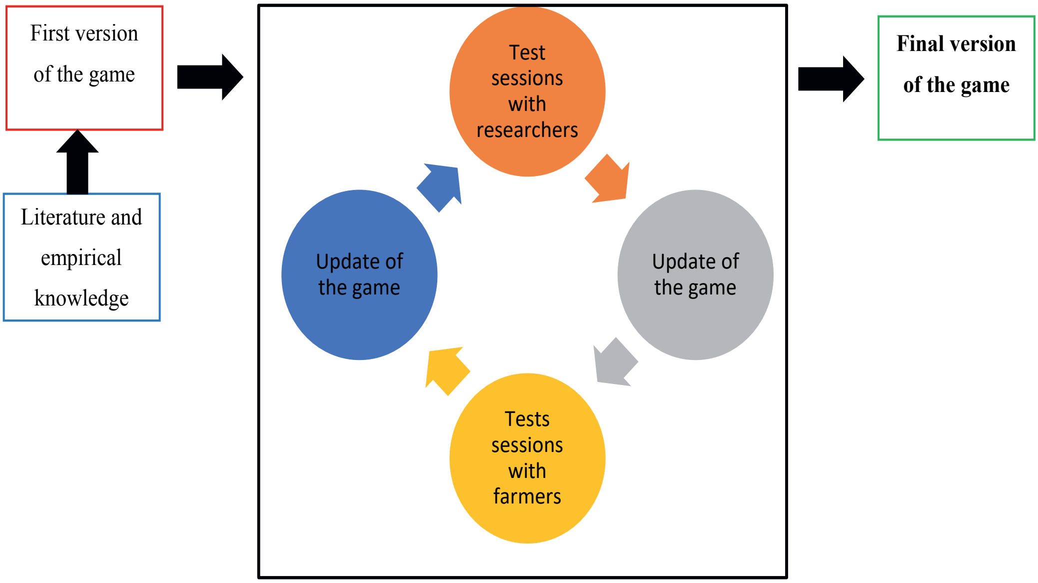


Figure 4.2: design process of the serious game QUEEN (QualitativE Evaluator of farm productioN).

Table 4.1: steps between the first development of the game and the final version used to collect data

Date and activities	Participants	Update of the game
December 2020: one test session	Researchers	Reduction of the steps in the game from 12 to 6.
January 2021: two tests sessions	Researchers	Simplification of rules on crop and livestock production as well as prices. Reduction of steps in the game from 6 to 3.
February 2021: one test session	Researchers and local agronomists	Game play adjustment: repartition of roles to facilitators. Adjustment of rules on inputs in fields and livestock selling: maximum 2 organic and mineral input per field. Unfed animals cannot be sold.
March 2021: two tests sessions	Farmers	Removal of rules on land cultivation according to labour availability. Adjustment of rules on free grazing on crop residues.
April 2021: two tests sessions	Farmers	Introduction of rules on seasons (rainfall) variability. Each season could be "good" or "bad".
April 2021: debrief meeting	Researchers	Fixed sequence of seasons for easier comparison between game sessions.
June 2021: conceptual update of the game	Researchers	New design of the game to include more than one crop and crops combination. Adjustments on crop production rules in relation to the type of season.
July 2021: four tests sessions	Farmers and local agronomists	Adjustment of prices and participants resources at the beginning of the game.
August 2021: two tests sessions	Farmers	Adjustment of rules on manure production by livestock.

4.2.2.2 *Game mechanics*

The rules of QUEEN are summarized in Box 4.1.

The game was played for five consecutive rounds, each round corresponding to one year. Each round consisted of three steps: sow, harvest and market. A fictive round was organized before each game session to help participants become familiar with the rules and ask questions. Four facilitators were involved in the game. Two updated crop and livestock production in the game, one reported statistics, and the last one bought/sold resources from/to participants.

In the first step of the game (sow), each participant chose seeds of crops they wanted to grow. Farmers could grow a maximum of two crops (intercropping) in a field. Participants could chose to apply intercropping and crop rotation, as well manure and/or fertilizer on each field. Fertilizer and manure could be bought if participants had enough cash. During the sowing steps livestock were parked on the grazing land, where they always met their feed requirement.

After all participants completed the first step, one facilitator announced the type of season which could be "good" or "bad" (see Dynamics section of 4.2.2.4). A series of seasons was randomly chosen and used in all sessions. The season was always "good" for the first, fourth and fifth round while it was "bad" for the second and third round. Likewise, the same initial conditions were used for all participants in every session.

In the second step (harvest), participants harvested all grains produced according to the inputs applied and the type of season. Each participant harvested the crop residues according to the available labor, determined by the family size, and the number of cows and/or donkeys (Box 4.1). All animals in the game could then graze freely on crop residues left on the fields, as it is commonly practiced in the study area.

The third step (market) was dedicated to buying and selling at the market. Participants could also exchange resources among themselves. Participants who could not meet their feed/food requirement could purchase additional crop residues/grains to feed their livestock/family. Unfed animals could not be sold.

Box 4.1: rules of QUEEN game

1. In a good season, each plot produces 2 units of grains and 2 units of crop residues.
2. A maximum of 2 units of manure/mulch and a maximum of 2 units of fertilizer can be applied on one plot.
3. In a good season, in strip intercropping, a plot produces 1 unit of grain and residue of each crop.
4. In a good season, in traditional sorghum-cowpea intercropping, a plot produces 2 units of grains and 2 units of crop residues of sorghum.
5. In a bad season, grain and crop residues production per plot is divided by half.
6. Plot production drops by half after two years of monoculture.
7. There is one additional unit of grain after two consecutive rounds of intercropping or manure application.
8. Attribution of additional grain/crop residues and production in bad year in intercropped plots: sorghum>cowpea>mungbean>sesame.
9. Manure provides one additional unit of grain and crop residues.
10. One unit of crop residues used a mulch provides one additional unit of grains.
11. Fertilizer provides one additional unit of grains and crop residues in good years and only one additional unit of crop residues in bad years.
12. All grains are harvested.
13. The number of units of crop residues a farm can harvest is function of its household size and number of cattle and donkeys. 2 people harvest one unit of residue, 1 cattle/donkey can be used to harvest 4 units of residues.
14. Cattle, donkey and sheep respectively require 4, 3 and 2 units of residues after harvest. Unfed animals die next round.
15. Livestock feed on unlimited grass in grazing land at the sowing step.
16. Livestock of all farms can feed on crop residues not harvested by participants.
17. A maximum of two animals could compete for crop residues on a field after harvest. If competition occurred, the dice was thrown to decide which animal would benefit from the crop residues.
18. Two cattle, 4 donkeys or 8 small ruminants produce 1 unit of manure.
19. Livestock reproduce in the third round. Two animals give birth to one. All animal types are concerned.
20. Each household member eats 2 units of grains per year (all grains except sesame). Participants get a penalty of two units of cash per unfed household member.
21. Prices of grains and livestock are different. Cattle, donkey and sheep are worth 10, 5 and 3 units of cash respectively. Sorghum, cowpea and sesame grains are worth 1, 2 and 2 units of cash respectively. Mungbean grains cannot be sold.
22. A unit of manure and a unit of fertilizer have the same price: 1 unit of cash. Two crop residues are worth 1 unit of cash.
23. Manure and fertilizer cannot be conserved for more than one round.

4.2.2.3 System description

The farming system components and relations that served as basis to the development of QUEEN included the four farm types present in the landscape (Figure 4.3). In each farm, households managed their livestock and fields to get grains, crop residues, manure and cash. Field management included the choice of crops, and the way they are managed (manure/mulch/fertilizer inputs, intercropped or not, in rotation), as well as crop residues harvesting. Livestock were fed with crop residues harvested or left on fields and forage in grazing areas. Several direct exchanges could occur between households and with the market. Farm resources that can be directly exchanged between households and in the market included manure, fertilizer, grains, crop residues, livestock and cash. Common resources considered in the farming system were crop residues left on soil after harvest and forage from grazing areas. Every livestock in the system could graze on crop residue left on fields or in grazing areas. The climate and the market were the only two external drivers considered. Climate influenced the system through rainfall which directly impacts crop production (see Box 4.1). Households could buy and sell resources (4.2.2.4) from the market, which we assumed to be unlimited.

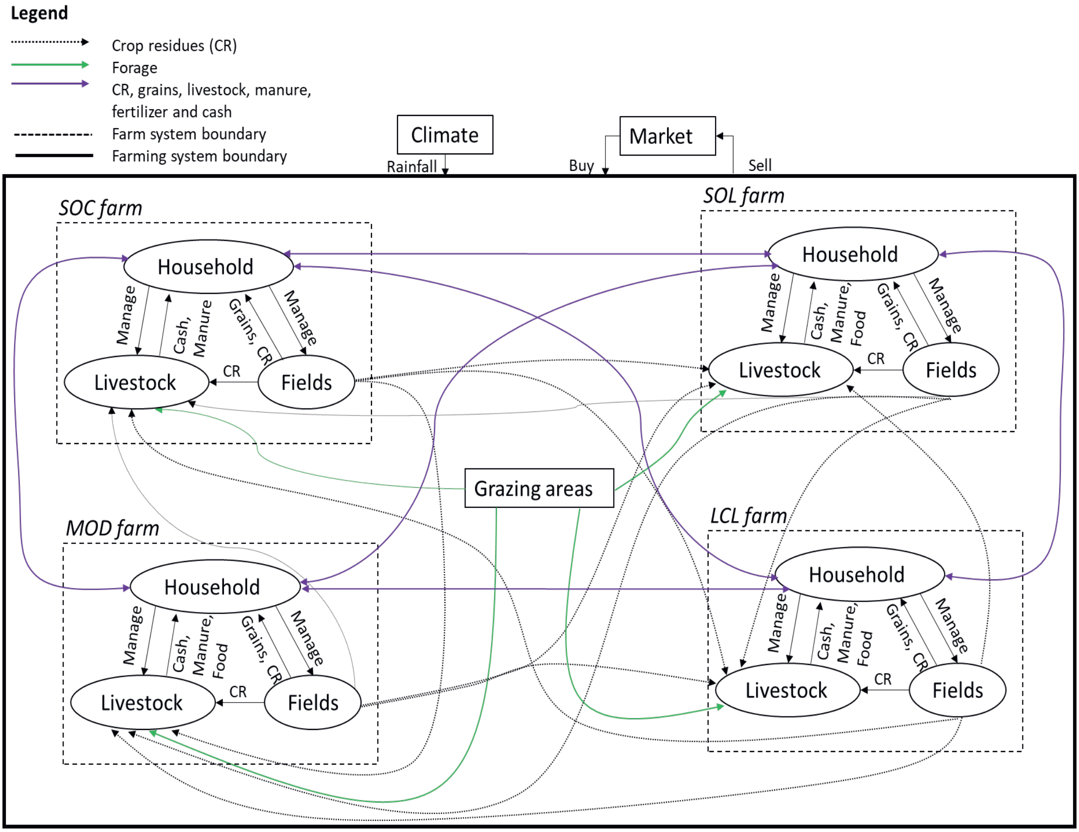


Figure 4.3: Representation of the four farming systems identified in the landscape (Assogba et al., 2022) used as a basis for the design of the player characteristic within of the game.

4.2.2.4 ARDI of the farming system and its implementation in QUEEN

Actors

The actors included in the farming system were farm households. QUEEN was designed with four participants representing the four farm types of the farming system. The participants involved in the development of the game as well as game sessions had already been surveyed and classified in different farm types (Assogba et al., 2022). Therefore, the structural characteristics (cultivated area and crops, herd size, family size and income) of participants' farms in the game were already known.

Resources

The resources of the farm system included the cultivated fields, livestock (cow, donkey and small ruminants), manure, fertilizer, seed and grains. In addition, we represented crop residues, forage in grazing land and cash. We considered sorghum, cowpea, sesame and mungbean as the crops.

Participants' resources differed according to their farm types. For example, SOC, SOL, MOD and LCL participants had respectively five, four, six and four cultivated fields of the same size. The resources at the beginning of each game session (Table 4.2) correspond to the average characteristics of each farm type.

Table 4.2: Resources allocated to each farm type at the beginning of a game session. SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock farms.

	Family size	Cows	Donkeys	Sheep	Poultry	Fertilizer	Grains	Crop residues	Manure	Money
SOC participant	5	0	0	2	0	0	0	0	0	1
SOL participant	4	0	0	4	0	0	0	0	0	1
MOD participant	6	2	1	2	0	0	0	0	0	2
LCL participant	4	5	0	2	0	0	0	0	2	2

Dynamics

Crop production in the study area only occurs during the unique rainy season and is a function of rainfall, seed, labor, manure, fertilizer and mulch. We assumed that crop production increases with organic (manure and mulch) and mineral inputs, but not to an unlimited extent (Gram et al., 2020). In addition, organic inputs limit soil fertility decline and support crop yield (Adams et al., 2020; Soma et al., 2018). This information on crop production was included in the mechanics and the rules of the game (4.2.2.2). In each round, fields in the game produced grain and crop residues as a function of rainfall and inputs (seed, manure, fertilizer and mulch) supplied by the participants. Rainfall was represented by the type of season which could be "good" or "bad". A "good" season referred to adequate and well-distributed rainfall throughout the season whereas a "bad" season referred to the opposite. To simplify the game, labor was not considered for crop production. However, labor was considered to determine the maximum amount of crop residues a participant can harvest (see Box 4.1). Yield loss due to prolonged monoculture (Bado et al., 2012) was included in the game as grain loss. In addition, benefits from cereal-legume intercropping and rotation (Franke et al., 2018; Ganeme, 2022) were translated in a grain bonus in the game (Box 4.1). Two types of intercropping were represented in the game, namely the traditional intra-hill intercropping (only for sorghum-cowpea intercropping) and strip intercropping (two lines of sorghum alternated with two lines of another crop).

Livestock production in the study area depends on grazing in rangelands that are common property of the communities (Assogba et al., 2023) and only produce grasses during the rainy season. Similarly, the grazing land in the game produced forage during the sowing period only. The amount of forage produced was assumed to always meet livestock requirements during that period. The contribution of trees and shrubs to livestock feeding in the dry season was not considered for simplicity. According to (Otte and Chilonda, 2002) the calving and lambing of cattle and small ruminants in mixed farm systems of SSA happens on average every two and one year respectively . In the game, livestock reproduction was simplified and only occurred in the third round of the game. Manure production from livestock increases with their weight (Assouma et al., 2018). In the game, a larger amount of manure is produced by cattle followed by donkeys and small ruminants. Manure production in the game only happened in the first round and for each participant manure produced by their livestock was automatically stocked in their farm and could later be applied to fields.

Although prices of resources varied within and across years in reality, they were kept constant in the game to simplify the playing process. Nevertheless, prices in the game reflected general patterns in the study area. For example, cattle was the most expensive livestock and cowpea had a higher price than sorghum.

Interactions

Interactions between farm households and resources were implemented in the game. Participants invested labor, seed, fertilizer and manure in their fields and harvested grain and crop residues that were used to feed their family and livestock respectively. Farmers could also buy and sell livestock as well as grains and crop residues. In the game, farmers were also free to discuss and exchange biomass (seed, manure, crop residues, grains and livestock), fertilizer and lend money to each other.

4.2.2.5 Game solution space

It is possible to numerically explore serious games through the solution space determination (Speelman et al., 2014). The solution space of a game can be defined as all the possible outcomes of the game. By unravelling the latter, it is possible to locate game participants' outcomes regarding the optimal outcomes.

To explore the solution space of QUEEN, a digital version of the game was created in Netlogo 6.2.1 (Wilensky, 1999). The digital version included four participants that can be human or automated. In order to explore the range of possibilities offered by QUEEN, a routine was set up to allow automated participants to play for a given number of sessions. In total 30000 sessions were run with four automated participants. We assumed 30000 automated sessions would be enough to capture all possible outcomes of the game in terms of food security, cash, and crop and livestock production. Initial resources allocated to each automated participant were the same as the ones used during the game sessions with farmers. Random decision-making was made by each automated participant on crop and livestock management, buying and selling of resources as well as exchange of resources. All possible options (e.g. buying and selling) in the game were available to automated participants at each step of each round of the game during the solution space exploration, i.e. there were no effect from last round on the option chosen for the current round.

4.2.3 Game sessions

Three game (pilot) sessions were organized from 17-11-2021 to 19-11-2021 in Yilou (one session) and Tansin (two sessions). Each session lasted 2.5 hours on average and involved four participants. Each participant took part in only one game session, so in total we had twelve participants. Volunteer farmers that participated in the game sessions were previously included in a database containing data on the resources of their farms (Assogba et al., 2022). Each participant played a farmer whose resources corresponded to the farm type the participant belonged to. Because the LCL farm type was only present in Yilou, in the two game sessions that took place in Tansin, LCL farms were replaced by SOC farms, which is the dominant farm type in Tansin.

4.2.3.1 Data collection and data analysis

During the game

Throughout the game sessions, we collected data on participants' cropping system and livestock management as well as exchange among themselves and with the market in every round. Participants decided which crops to grow, how much fertilizer, manure and/or mulch to apply, and if they intercropped or rotated their crops. Grains and crop residues harvested, purchased, sold and/or exchanged were also recorded. Livestock (cattle, sheep and donkey) sold, purchased and dead from starvation were also recorded. We also kept track of the number of household members that could not be fed and the cash available for each participant at the end of each round.

After the game

After each game session, a post-game questionnaire (supplementary materials) was used to collect information on participants' experience during the session. The post-game questionnaire was used right after each game session and aimed at collecting data on: (1) participants' objectives during the game and if and how they achieved them or not and why, (2) actions implemented during the game and how these differed from reality, (3) how participants influenced each other during the session, and (4) what participants learnt and their recommendations to improve the game.

Data analysis

The game sessions outputs were analyzed per round, per participant and per farm type. Average values were computed for resources per farm type, except for the single LCL participant who was involved in the sessions. These statistics concerned inputs (seeds, manure, fertilizer and mulch) and grain and crop residue production and harvest per field. Inflow and outflow of grains, crop residues, manure and money at the farm level were also included.

Based on the data collected with the questionnaire after each game session, we analyzed participants' goals, their strategies and the degree of realism of the game. We qualitatively described the diversity of participants' goals. In addition, the proportion of participants using a given strategy was computed. To analyze the degree of realism of participants' decision-making during the game sessions, we calculated the proportion of participants that reported they would have used a different strategy in real-life and we qualitatively analyzed what they would have done differently. In addition, we qualitatively assessed the realism of the game itself based on participants' feedback on what was missing in the game in comparison to real-life. Moreover, we summarized what participants reported they learnt from the game sessions.

From the solution space exploration, linear correlations were computed to assess possible trade-offs or synergies between outputs of the game. For example, the relation between the amount of cash and the number of food insecure member in a household. Correlations were computed for the last round of the game between outputs, such as the number of cattle, sheep and donkey, the amount of cash, grain harvested and remaining grains in stock. Correlations were computed per farm type and for all participants. In addition, probabilities of occurrence of the simulated game outputs values were also analyzed. This helped to analyze how likely a participant can end with a given amount of each resource (cash, cattle, donkey, small ruminants, grains and crop residues).

The outcomes obtained by the real-life game participants were projected in the solution space of the farm type they belong to. The objective was to check whether and how participants' outcomes fitted in the solution space. Moreover, based on the game goals of increasing crop and livestock production and cash, we defined the optimal simulations as those with cash, crop and livestock related output values comprised between 0.75 and 1.25 times the 99% percentile value from the solution space. An additional requirement for the optimal simulations was that all households' members received the required amount of food during each of the five rounds. The strategies and outcomes of the real-life game sessions and the optimal simulations outputs were compared.

4.3 Results

4.3.1 Game session results

4.3.1.1 Farm management during game sessions

The cropping system during game sessions was dominated by sorghum, occupying on average 45% of plots (Figure 4.4). Land allocation to crops varied among participants and was not related to the farm type. For example the SOL participant in the first game session dedicated half of plots to sesame whereas the SOL participant in the second session mainly chose sorghum and cowpea. Land allocation to crops remained constant for most participants throughout rounds. The second most cultivated crop was cowpea (34% of plots) followed by sesame (17% of plots). Cowpea and mungbean were often (in 63% of plots) intercropped with sorghum using the strip intercropping practice. The traditional sorghum-cowpea intercropping was applied only in 5% of plots on average. MOD participants had the highest number of plots and also had the most diversified cropping system. The LCL participant, cultivating the smallest number of plots (together with SOL), had the least diversified cropping system which consisted almost only of sorghum and cowpea. The newly introduced mungbean crop was rarely included by farmers in their cropping system.

Manure and fertilizer were frequently applied by participants in each round. Manure and fertilizer applications occurred respectively 59 and 45 times over 60 possibilities (Figure S1, Appendix 3). Mulch application occurred only 29 times over 60 possibilities in the three sessions. Fertilizer and organic (manure and mulch) inputs were mostly applied to sorghum (95%, 91% and 60% of fertilizer, manure and mulch applied resp.). On average, respectively 56 and 23 units of organic inputs and fertilizer were applied per game session. The total amount of organic inputs and fertilizer applied in each session was still far below the maximum achievable given the rules of the game (190 units of manure/mulch and 190 units of fertilizer) (Table S1, Appendix 3).

Participants mainly purchased grains in bad years, i.e. in rounds two and three (Figure 4.5a). Only sorghum grains were purchased. SOC and SOL participants in the first session had a cropping system dominated by sesame and purchased grains more frequently. However, they also sold most grains (especially sesame) per capita. For all participants, grain selling occurred mainly in the good years, especially in rounds four and five, and for the most part concerned cowpea and sesame.

Livestock purchase and sale were rare compared to grains (Figure 4.5b). Contrary to grains, livestock was largely sold in bad years. Small ruminants were the most frequently sold animal type. Similarly, livestock purchase mostly concerned small ruminants and occurred in the last (fourth and fifth) rounds of the sessions.

The purchase of crop residues was frequent in the first game session, especially by SOC and SOL participants that had a crop system dominated by sesame which crop residues could not be grazed by livestock in the game (Figure S2, Appendix 3). Additionally, MOD (in sessions 1 and 3) and LCL (in session 3) purchased crop residues mostly in bad years. Crop residue sales were rare and occurred the most in the fourth and fifth rounds.

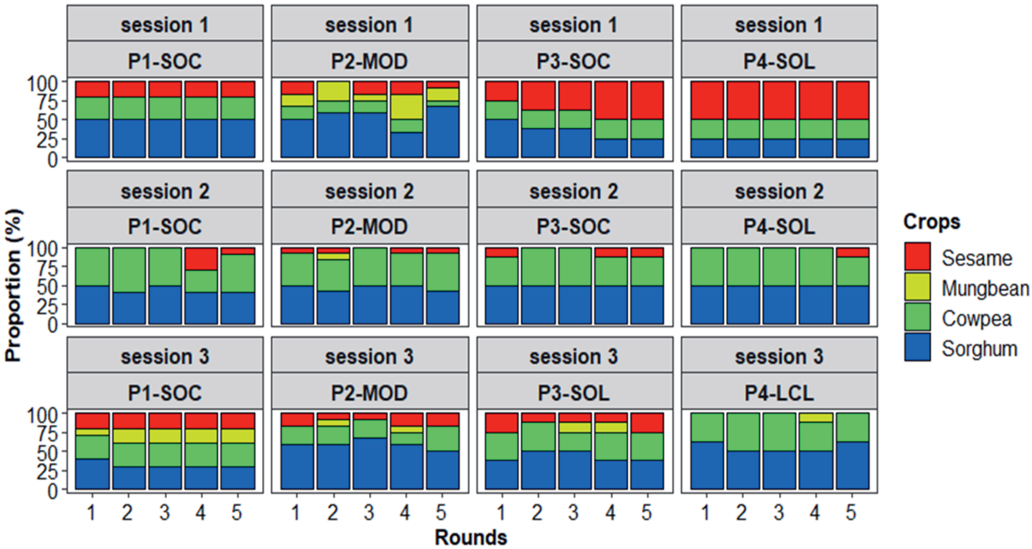


Figure 4.4: Crop allocation to different plots. SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL). P1, P2, P3 and P4 refer to the four participants of a game session.

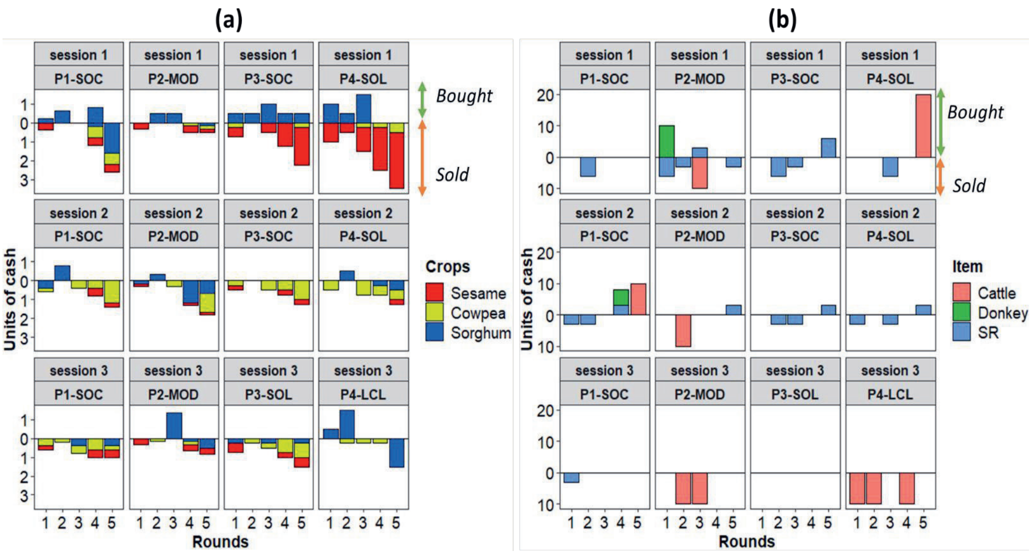


Figure 4.5: values of grains per capita (a) and livestock (b) purchased and sold during game sessions. SR = small ruminants. SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL).

4.3.1.2 Participants' strategies during game sessions and their perceptions of the game

When asked at the end of the game session, participants' objectives were not the same (Table 4.3). Actually, while some were trying to increase their cash and/or crop/livestock production, others were trying to simply maintain their resources (cash, grain, manure, crop residues, and livestock) or simply feed their family. 42% of participants said they reached their objective in the game. The strategies participants used to reach their goals also varied. The use of strip sorghum-legume intercropping was the main strategy reported. Indeed, 58% of participants reported they used strip sorghum-cowpea/mungbean intercropping to reach their goal. In addition, 42% of participants reported grain selling as their strategy to get cash.

Participants reported differences between what they did in the game sessions and what they actually do in real life. Three participants reported not selling grains, especially sorghum grains in real life. In addition, in the game, some participants increased the share of land dedicated to sesame beyond what is really done as four of them reported focusing much more on sorghum and cowpea in reality. Two participants reported they would have applied the traditional intra-hill sorghum-cowpea intercropping rather than the strip intercropping. On crop residues management, most participants agreed on harvesting a higher share of crop residues in reality than what happened in the game which was limited by the number of big ruminants and household size. While 92% of participants applied mulch at least once in their fields in the game sessions (Figure S1, Appendix 3), only three participants (2 SOC and 1 SOL types) reported applying mulch in real life. Free grazing on crop residues left on fields after harvest was not seen as a problem for most (75%) participants. However, they also reported that livestock in free grazing let some manure in their fields which was not included in the game. Interestingly none of the participants reported selling livestock as part of their strategies. Even if most participants' reported after the game that they exchange seeds, grains and crop residues in real life, only three cases of biomass exchange was noted between participants in the sessions. Indeed, during the game sessions, exchange of items between participants were rare and only concerned crop residues given away (two occurrences) and exchange for money (one occurrence).

Concerning "lessons" learnt from the game session, participants mainly reported they learnt about the benefits of intercropping especially in bad seasons. Some participants also reported they learnt about farm management in bad seasons without being specific about it. Only one participant reported learning about crop rotation despite crop rotation being applied by all participants during the sessions.

Table 4.3: game participants goals, strategies and perception of game sessions. P1, P2, P3 and P4 are respectively participant 1, participant 2, participant 3 and participant 4. SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL). IC = sorghum-cowpea/mungbean intercropping. Ica, IG, IR, IL stands respectively for: increasing cash, grains, resources and livestock. Resources refers to cash, grain, manure, crop residues and livestock. FF = feed family. MR = maintain resources.

Session	participant	Goal	Strategy	Goal achievement	What the participant would have done differently in real-life	Perception on free grazing on residues on soil in the game	What the participant could have done differently on crop residues management	Mulch in real life?	Real life biomass exchange	What participants learnt
1	P1 - SOC	IR	IC Selling grains surplus	no	Not selling sorghum but a bit of cowpea.	No problem	Leave less crop residues on field		I no more exchange crop residues (with manure) as the pastoralists moved southward due to bad rainfall	Farm management
	p2 - MOD	Ica	IC	yes		No problem	Share residues on soil in fields with other farmers Use crop residues for compost		I exchange my seeds to get better seeds	IC to save harvest in bad years
	P3 - SOC	MR	IC Selling grain surplus and livestock	yes	Cultivate more sorghum. Apply traditional intra-hill intercropping and more fertilizer.	No problem	Leave less crop residues on fields in bad years		Crop residues send away to relatives	Farm management especially in bad years
	P4 - SOL	IG Ica	IC Rotating 2 years of sorghum-cowpea intercropping with sesame to get some cash	yes	Same thing if I have similar resources in real life.	Livestock should left some manure in fields.	Feed my livestock to get manure		Exchange sorghum residue to get peanut/cowpea residues	Crop rotation
2	P1 - SOC	Ica IG	IC	yes		Good practice.	Share crop residues on soil in fields	Yes, in real life, I return my crop residues to fields	I exchange seeds, manure or crop residues when I am in need	How to manage bad seasons
	P2 - MOD	IG IR IL	IC Applying manure to plots	yes	Traditional intra-hill intercropping instead of strip intercropping. No grain selling.	A reality in the village. Livestock leave manure on fields.	Leave part of crop residues on fields and sell a small fraction			The game promoted strip intercropping. I also learned how to manage a bad season

Session	participant	Goal	Strategy	Goal achievement	What the participant would have done differently in real-life	Perception on free grazing on residues on soil in the game	What the participant could have done differently on crop residues management	Mulch in real life?	Real life biomass exchange	What participants learnt
	P3 - SOC	FF Ica	IC Growing sesame Selling cowpea and sesame grains	no	No real difference. In reality, I do not have enough manure and fertilizer. I apply fertilizer in fields that did not receive manure.	Not a problem. Livestock from other farms leave manure in return of grazing.	Feed my livestock and turn the fee refusal into compost	Yes, when it rains well, there are big stalk not easy to cut.	I give away grains	Strip sorghum-cowpea intercropping.
	P4 - SOL	Ica IG (sorghum, cowpea and sesame)	Buying and applying manure and fertilizer	yes	I would focus on sorghum and cowpea	Good practice	Share residues on soil in fields	Yes, in real life, I return my crop residues to fields	I exchange seeds to get early maturing seeds	I learnt about the advantages of intercropping
3	P1 - SOC	IR Good management of my farm	By maintaining the same cropping system and only practicing intercropping	yes		I do not completely agree. Livestock of the farm should eat first.	I would stock a big share of my crop residues at home			The game is quite realistic, it is good. I allows to understand farm management during the season. It allows to better plan for a better farm management.
	P2 - MOD	IL	Harvest enough grains and sell	no	I would only grow sorghum and cowpea	It is a good practice.	I would have harvested more crop residues		I do not exchange biomass because it is not a common habit	A mind-awakening game in farm management
	P3 - SOL	Manage my farm	Selling grain and livestock and cultivating mainly sorghum	yes	Not selling sorghum grains	Good. This practice helps farmers to alleviate their crop residues constraints	I would stock more crop residues at home and exchange with pastoralists.		I do not have a big herd in real life, so I exchange my crop residues for manure	The game was realistic and allowed to anticipate on farm management et prevent hazards that can happen during the season.
	P4 - LCL	IR	Growing sorghum, cowpea, sesame and applying fertilizer	yes	I would only grow sorghum and cowpea	It is a good practice.	Agreement with other farmers so that all animals are fed.		Yes, if we are lacking crop residues	I learned about new farm management practices.

4.3.2 Game solution space

Linear correlations between game's outputs at the end of all rounds were negligible (Figure S3, Appendix 3). In other words, there were no clear tradeoff between outputs and we found no evidence that the maximization of an output (e.g. livestock) were in synergies, or to the detriment of another output (e.g. crop production). The exploration showed limited number of cattle could be maintained at the end of the game. Indeed, the game exploration revealed that a maximum of 6 cattle could be kept by each participants at the end of the game. However, the maximum of cattle was only observed 5 times during the exploration corresponding to only 1/1000 chance of occurrence. There was higher chances to have less cattle in the game. In fact, it was more likely (99%) for each participant to end up with zero to two cattle at the end of the game. The solution space exploration also showed that it was not possible for each participant in the game to have both relatively high number (from four to six) of cattle and cash. The same applied for cattle and donkey as well as cattle and small ruminants. The average cash, small ruminants and donkey owned by each game participant with a number of cattle greater than four was respectively: 3.74 (min = 0 and max= 83.9), 1.8 (min = 0 and max= 25) and 1.1 (min = 0 and max = 23).

Similar to cattle, the median (and thus the most probable) number of small ruminants at the end of the game for each participant was one, the minimum being zero and the maximum was 25. Ninety percent (90%) of simulated game sessions resulted in a number of small ruminants comprised between 0 and 3. Highest values (superior to 15) of the number of small ruminants were rare (0.075% of occurrence) and associated with relatively small amount of cash (4.3 on average) and donkey (1.47 on average). The median number of donkey per participant at the end of the game was zero. Ninety percent of the simulations resulted in a number of donkey between 0 and 2 for each participant. Ninety eight percent (98%) of simulations led to zero food unsecure household member (in the game) for each participant.

4.3.2.1 Farmers' outcomes VS solution space

The projection of individual real-life participants' (RP) outcomes in the solution space of the game allowed comparison between RP and automated participants (AP) in terms of cash, crop (grain and crop residues) and livestock value (Figure 4.6a and Figure 4.6b). On average, the crop value of individual AP was higher than individual RP (35 and 24 units of cash for AP and RP resp.). On the opposite, the average livestock value of individual AP (6 units of cash) was far lower than individual RP's (19 units of cash). Similarly, the average cash of individual AP (5 units of cash) was also lower than individual RP's (15 units of cash).

Likewise, considering each game session and each optimal simulation, the crop values of AP was always higher than RP's (168 and 98 units of cash on average for game sessions and optimal simulations resp.) (Figure 4.6c). The average livestock value of game sessions and optimal simulations were not significantly different (83 and 77 units respectively) (Figure 4.6d). In addition, the game sessions yielded more cash than the optimal simulations (58 and 39 units of cash resp.). However, the combination of crop and livestock value as well as cash was superior for optimal simulations (292 and 252 on average for game sessions and optimal simulations resp.).

Interestingly, both individual RP and AP (in optimal simulations) did not have individual best combination of crop and livestock production and cash. As optimal simulations were based on aggregation of individual participants' resources, this suggests that collective optimal outcomes was not dependent on optimal combinations of crop, livestock production and cash at individual participant level. Moreover, even if participants in game sessions reported different goals and strategies (Table 4.3), the outcomes of the three game sessions were not significantly different in terms of cash, crop and livestock value.

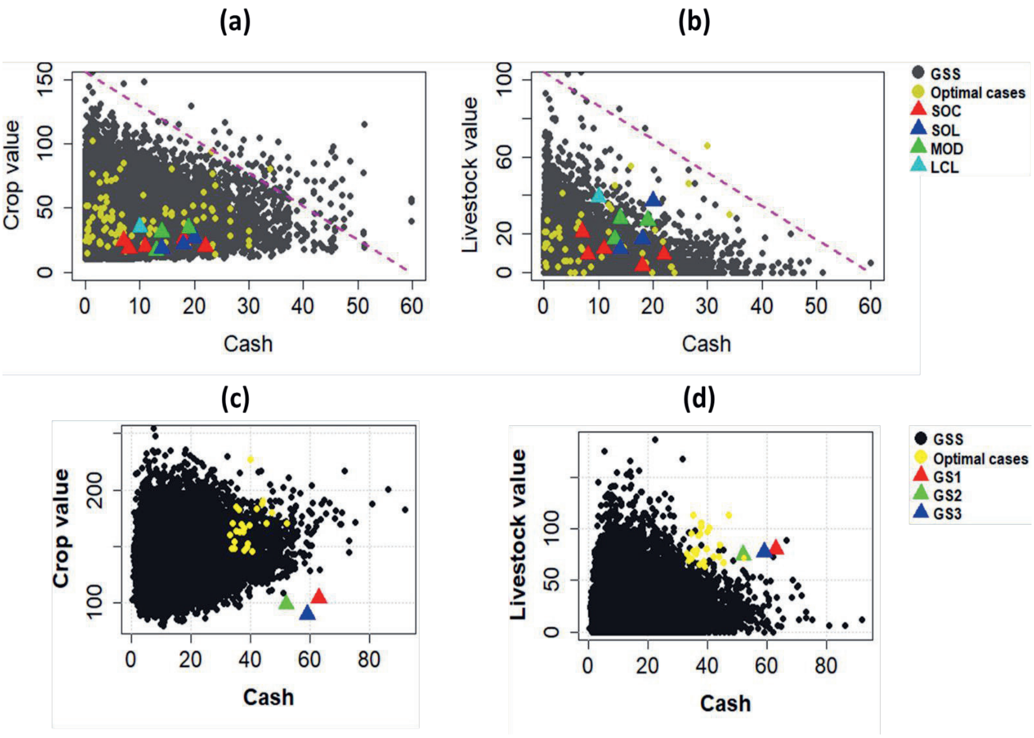


Figure 4.6: projection of each real-life participant outcomes of the game sessions in the solution space (a, b). Projection of outcomes of all real-life participants of each game sessions in the solution space (c, d). Only the last (fifth) round of the game is considered. GSS = Game solution space exploration results for each automated participant. Optimal cases = automated participants in the best simulations of GSS regarding crop, livestock production and cash. GS1, GS2 and GS3 are respectively results of game session 1, 2 and 3. Yellow points are the best compromise between crop, livestock and cash, from game space exploration. SR = small ruminants. Participants farm type: SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL). The dashed line in magenta symbolically represents the maximum of each plotted variables that can be obtained in combination for individual participants.

4.3.2.2 Farmers' strategies VS theoretical best compromise between crop, livestock and cash

The cropping system in the optimal simulations was different from the game sessions as plot allocation was similar for all crops (Figure 4.7a). Inputs (fertilizer, manure and much) were mainly applied to sorghum and cowpea. The cropping system setting remained the same from the first round to the last one. Only the share of plots with sorghum-legumes (cowpea/mungbean) intercropping increased slightly but was inferior to RP's. The total amount of fertilizer applied in the optimal simulations was similar to the one observed in game sessions (Figure 4.7b). The total amount of manure applied during the game sessions by RP was always higher than AP's, except for the first round. Interestingly AP applied more than the double of mulch applied by RP in game sessions. Indeed, the advantage of applying mulch in the game was additional grain and the price of crop residue to be applied as mulch was half of the one of fertilizer and manure. Therefore, by applying one unit of residue (0.5 unit of cash) as mulch it was possible to get one to two units of cash depending on the cultivated crop. In comparison, applying one unit of manure or fertilizer (1 unit of cash), it was possible to get a crop value of 1.5 to 2.5 units of cash. Hence, the cost benefit ratio of applying a unit of mulch (0.25-0.5) was much lower than manure/fertilizer (0.4-0.67).

In optimal simulations, manure, fertilizer and crop residues were frequently purchased (Figure 4.8a). Additionally, sheep was purchased by all farm types and LCL participants sold cattle to purchase donkey in the first round. However, items' selling was in general less important and mainly concerned grains harvested and donkey. In the optimal simulations, many exchanges of resources occurred between participants in each round (Figure S4a, Appendix 3) whereas in the game sessions, exchange of items between participants were seldom. The number of items exchanged increased with the number of rounds. On average, manure, fertilizer, grains and crop residues were sent away and received by SOC and SOL AP respectively. (Figure S4b, Appendix 3). In the last round of the game, there were on average almost no cattle in the game (Figure 4.8b). Cattle were most likely replaced by donkeys. SOL and LCL AP had the highest number of donkeys whereas SOC and MOD AP had the highest number of small ruminants. On average, SOL and LCL AP had the highest livestock values (28 unit of cash) followed by MOD and SOC (26, 19 and 11 units of cash resp.). MOD and LCL AP had the highest grain harvested and cash. Therefore, the distribution of cash, crop and livestock values per farm types in optimal simulations differed from RP outcomes. Indeed, RP outcomes led to no clear difference in cash and crop values per farm type (Figure 4.6a). Moreover, from RP game sessions, the distribution of livestock values at the end of the game remained similar to the beginning (Figure 4.6b). Another important difference between RP and optimal AP outcomes was that RP maintained cattle in their livestock system and did not increase their number of donkeys (data not shown).

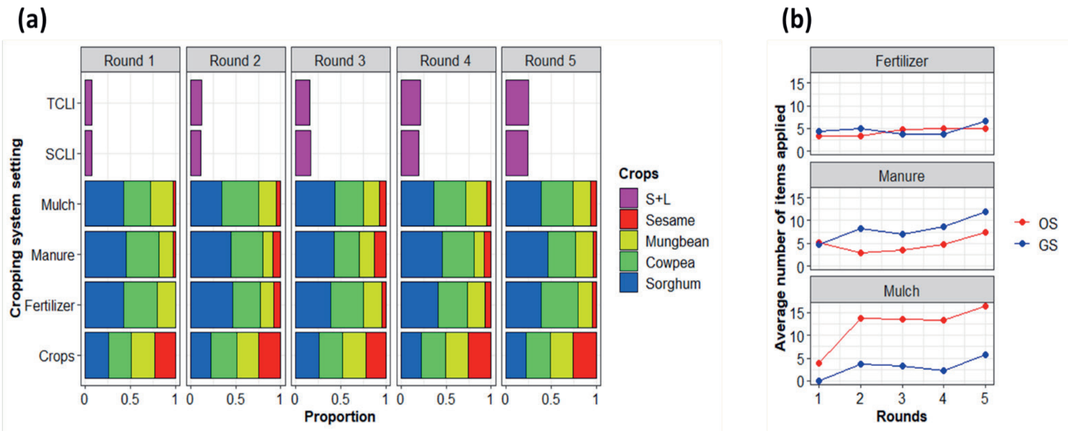


Figure 4.7: cropping system setting of optimal simulations from game solution space (a). Comparison between average inputs (fertilizer, manure and mulch) applied by all participants in game sessions (GS) and optimal simulations (OS). S+L = Sorghum and Legumes (cowpea/mungbean).

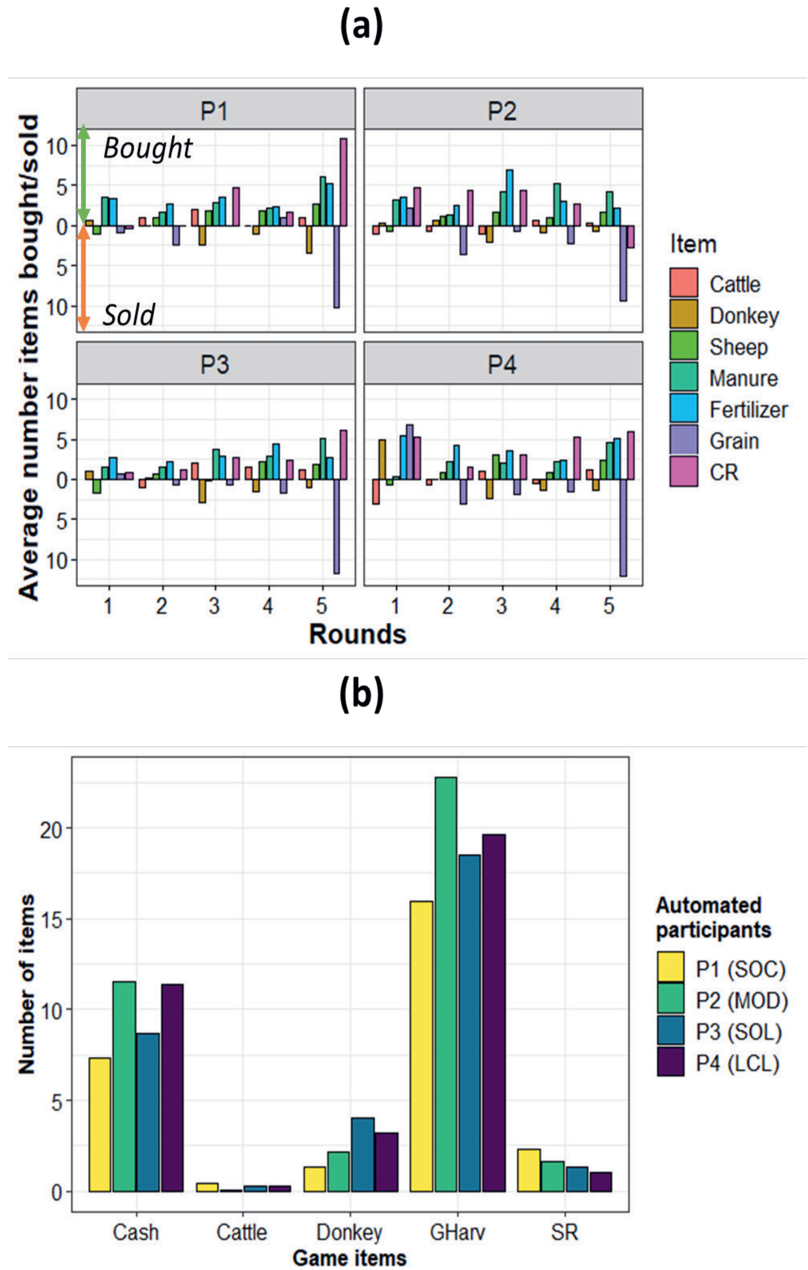


Figure 4.8: patterns of game simulations in the solution space exploration leading to best compromise between crop, livestock production and cash. Average number of items bought and sold (a). Average number of items owned at the end of optimal selected simulations representing the best compromise between crop, livestock and cash (b). P1, P2, P3 and P4 are automated participants. Participants farm type: SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL).

4.4 Discussion

4.4.1 Differences between game and real-life behavior

Objectives of participants in the game differed from the objectives stated by researchers at the beginning of the game. This highlights the importance of clarifying the goals of the game and making sure participants all understand it prior the start of the game. Additionally, the debriefing sessions using a post-game questionnaire were essential to understand what happened in the game. Indeed, participants' goals in the game have a strong influence on what they actually do in the game sessions. For example, from the solution space exploration we showed that it was possible for real-life participants to further increase crop inputs, like mulch. Indeed, during the game sessions, participants did not systematically use their cash to purchase crop inputs or resources in general, but rather spent the least possible and kept the remaining cash. This may be linked to participants' goals which were in general to increase their resources, and especially cash.

The questionnaire applied at the end of the game sessions revealed the level of realism of participants' choices during the sessions. Indeed, grain and crop residues production in the game was simplified. In reality, the cropping system is dominated by locally grown cereals such as sorghum and millet that generally produce more grains and crop residues than legumes. In real life, the share of land dedicated to cereals, especially sorghum, was slightly higher than observed in the game (Assogba et al 2023). Nevertheless, the cropping system configuration applied by participants during game sessions was still close to reality with dominance of sorghum and cowpea. The higher share of land dedicated to cash crop (sesame) in the game was probably due to its relatively high selling price in the game. Indeed, sesame cultivation is not so common in reality and farmers usually grow it to get some cash right after the harvest. The newly introduced mungbean was barely used in the game despite it being part of demonstration trials in which participants were involved. There are two possible explanations for the lack of inclusion of mungbean by participants in the game sessions. First, mungbean grains could only be used for consumption and its residue could not to be fed to livestock in the game. Hence, it does not offer additional advantages compared to other crops in the game. Second, mungbean is a new crop in the study area with no established market. In addition, appropriate processing of mungbean grains as food still needs to be studied and popularized. Contrary to mungbean, strip intercropping which is not practiced in real life by farmers (Ganeme et al., 2021), was applied by game participants. Indeed, mainly traditional intra-hill intercropping is applied in real-life. The participants may have applied strip intercropping in the game to get additional bonus within a year whereas the bonus from traditional intercropping was received only after two years of applying the practice. Likewise, all participants in the game sessions applied crop rotation but in reality crop rotation is barely practiced in the study area (Ganeme, 2022). Again, the rules included in the game probably motivated farmers to apply crop rotation to avoid penalties from monoculture. Similarly, some participants applied mulch in their fields in the game even if mulch application is rare in the region due to high pressure of livestock on crop residues (Assogba et al., 2023).

Livestock selling was rarely observed in the game sessions. In addition, no participant reported livestock selling as part of strategies to increase/maintain their resources. In real life, livestock keeping serve multiple purposes including manure, labor, social status, and cash (Molina-Flores et al., 2020). Mainly because of poor feeding, livestock production remains extensive with poor zootechnical performances (Otte and Chilonda, 2002). Because livestock value is not only related to productivity (meat and milk), participants chose (in real-life and in the game) to keep as much livestock as they can even if they have to rely on purchasing crop residues to feed their animals.

Even though there were possibilities of exchanging items, participants' interactions were more verbal and direct exchange of items remained limited. No communal management of resources was observed as participants were mostly focused on achieving their goals alone. The lack of biomass (e.g. crop residues and manure) exchange between farms, especially livestock and crop oriented farms, has already been reported in the study area (Assogba et al., 2022). Indeed, farms in the study area do not produce enough feed for their livestock and their grain yields remain modest with limited organic and mineral inputs. This significantly limits possibilities of exchange between farms. Although in the game it was possible to try new farm systems settings (e.g. moving toward more specialized farms), participants remained focused on their own farms and goals. Therefore, other game sessions are required specifically focused on the collective re-design of the farming system. These sessions can be based on already identified re-design options through the exploration of the solution space of the game.

4.4.2 Game solution space exploration.

The solution space was useful in identifying theoretical strategies leading to outcomes that are ideal with respect to the game goals. It was interesting to note that computer strategies, even if their differed from farmers' led to similar outcomes for participant resources. The theoretical farm management strategies suggested by the optimal simulations of the solution space implied a re-design of the actual farm system that comprised (1) increasing mulch and the share of land allocated to legumes; (2) decreasing the number of small ruminants and cattle; (3) replacing cattle by donkeys to lower feed requirements of the herd and (4) strong dependence on market to get crop residues. The results of the optimal simulations obviously depend on the simplifications made in the game to facilitate its playability. Indeed, in real-life a significant decrease in the area allocated to sorghum would decrease the amount of grains and crop residues produced to feed the household and the herd, whereas this is not the case in the game where all crops produce the same amount of grain and crop residues. Another assumption that explains the strategies of ideal simulations of the solution space is the unlimited availability of resources, and particularly crop residues, in the market. In reality, crop residue production is limited in semi-arid Burkina Faso and only a small fraction of crop residue produced is sold by farmers (Assogba et al., 2022). Therefore, massive purchase and application of crop residues as mulch is not a realistic scenario. Additionally, mulching would only be effective if farmers could fence their fields which is unlikely with their limited livelihoods. Not to mention that fencing would also increase feed scarcity for large livestock owners. In the livestock system, decreasing herd size, especially in crop oriented farms, is theoretically possible but due to multiple services and the social value attached to livestock keeping, especially cattle, the feasibility remains limited. Therefore, even if the optimal simulations were theoretically possible, their implementation in reality is difficult. The solution space exploration revealed the extent to which assumptions and simplifications in a serious game can affect potential outcomes of the game.

In addition to the assumptions and rules, the optimal solutions are also dependent on the management options included in the game. Because games are simplification of reality, the inclusion of farmers in the exploration of the farming system with various options is key to reflect on the practical side and feasibility of game outcomes. One advantage of solution space exploration is to identify desirable and achievable game outcomes and reflect with participants on how to possibly reach them in reality.

4.5 Further use and improvements of QUEEN

The present study was limited to the design of the game, few sessions with farmers, and exploration with the solution space. Beyond these steps, a serious game can be used for co-design of farming systems leading to practical management plans through scenario definition and analysis. One example is the Dynamix serious game developed by (Ryschawy et al., 2022) for crop-livestock integration in French farms. The authors combined their serious game and a farm model in participatory scenario building sessions, leading to concrete scenarios supported by research.

Further use of QUEEN could explore the effects of intensified collaboration between participants on the farm resources. In addition, the game could be explicitly directed towards the exploration of scenarios based on more diverse baskets of options (Ronner et al., 2021) to be tailored per farm type considering complementarity between crop and livestock oriented farms. The game can also be modified according to specific research questions, for example considering hybrid and/or dual purpose varieties and related seed prices and crop nutrient requirements as well as livestock movement outside villages in search for forage and its implication for organic matter availability.

In the current version of the game, labor (apart from crop residues harvesting) and off-farm income are not included. However, labor is a key factor influencing technology adoption by farmers and could be included in a future version of QUEEN. Additionally, possibilities of income diversification through off-farm activities could be added to analyze their impact on the farming system. Nevertheless, adding new elements and rules to the game may require simplifications in the representation of the farming system depending on the research question. Indeed, maintaining the playability of the game is key to facilitate communication with farmers.

4.6 Conclusion

We developed a serious game (QUEEN) to explore mixed crop-livestock farms of West-Africa. QUEEN is based on the local reality of farmers regarding their crops, livestock, and financial status as well as climate and market opportunities. The game included knowledge on soil fertility management, crop management, livestock mobility and feeding and market prices. We identified, using a post-game questionnaire, that participants' goals in the game differed to some extent from what was stated by researchers before each game session. In addition, using the same questionnaire, we were able to clarify between decision-making during the game and what participants applied in real life.

A computer version of the game was developed to explore the solution space of the game. The solution space exploration was useful at identifying relations between outputs of the game as well as the range of possible outcomes and their probability of occurrence. Additionally, by projecting the results of the game sessions in the solution space we were able to determine the individual and collective position of participants regarding ideal combinations of grains harvested, livestock and cash.

QUEEN can be easily adapted to other mixed crop-livestock systems based on local data. The game does not focus on a particular component of the farm system but aims at providing a holistic view and analysis of farm systems. It is a useful tool to foster communication among farmers and between farmers and researchers, because it functions as a virtual laboratory in which farmers are actors rather than spectators and actively share their perceptions and understanding of their farming system.

4.7 Acknowledgements

We thank farmers, agronomists and researchers from Burkina Faso, France and Netherlands who helped in the design and test phases of QUEEN. Special thanks to Nock Ouedraogo, Touwende Sawadogo and Souleymane Sawadogo and Boureima Sawadogo who facilitated the game sessions. We thank the McKnight foundation which funded this research through the 3F (Feed the soil and Feed the livestock to Feed the people) project. We also thank the CUOMO foundation for providing additional scholarship.

5 Crop diversification with legumes improves soil fertility but compromises food sufficiency at farm and village level: results of an agent-based modelling study in semi-arid Burkina Faso

Abstract

Crop diversification with legumes is often presented as a promising pathway to improve soil fertility and increase land productivity in sub-Saharan Africa. However, little is known about the impact of crop diversification with legumes at farm and specifically at village scale. In the present study we developed an agent-based model (ABM) to explore impacts of legume diversification on biomass production and flows, households' food sufficiency and income, as well as nutrient balances and use efficiency at farm and village scale in semi-arid Burkina Faso. We explored the model functionality with a sensitivity analysis and a pattern space exploration (PSE). The latter was used to assess synergies and trade-offs associated with crop diversification at farm and village scale. Our results confirmed current farm management leads to soil fertility mining at farm and village scale. We also found that food sufficiency could be reached at village scale but not always at farm scale despite exchange of grains between sufficient and non-sufficient farms. Moreover, we showed that village scale outputs were not just an aggregation or weighted average of farm scale outputs but depended on interactions between farms. The sensitivity analysis revealed that village scale outputs of the model were sensitive to parameters influencing both crop (rainfall and nitrogen) and livestock production (feed intake and reproduction). However, at farm scale the influence of parameters was often stronger than at village scale and varied according to farm types. The PSE results revealed that with the current level of nutrient inputs, crop diversification with legumes implied a trade-off between soil fertility on the one hand and food sufficiency and herd size on the other hand. This trade-off was stronger at farm scale than at village scale, and most strongly felt in the subsistence farms. In addition, the current cropping system configuration targeted short-term food sufficiency at the expense of soil fertility and led to high dependence on grazing land to feed livestock. We conclude that crop diversification associated with appropriate nutrient inputs can improve soil fertility and long-term food sufficiency. Further studies can use the model to investigate alternative social and spatial organizations at village scale.

Keyword: legumes, soil fertility, food sufficiency, multiple-scale modelling, model exploration.

5.1 Introduction

Agriculture in semi-arid West-Africa is dominated by subsistence farms (Giller et al., 2021) that often combine crop cultivation with livestock keeping. Livestock feed on crop residues and produce manure which is accumulated to later be applied to fields. Keeping livestock in addition to growing crops is also a livelihood diversification strategy of farmers. However, crop-livestock integration has been so far limited because of extensive rather than intensive crop and livestock production. Indeed, the application of inputs (nutrients, water and labor) and input use efficiency remain far from optimal mainly because of various constraints that are related to poor farmers' livelihoods (FAOSTAT, 2022; Svendsen et al., 2009; Zakari et al., 2014). The resulting yield gaps in food and feed production translate into food insecurity prevalence (van Ittersum et al., 2016) and high pressure of livestock on crop residues which could otherwise be used for soil fertility improvement through mulch (Assogba et al., 2022; Fraval et al., 2020). Consequently, farmers heavily rely on free grazing to feed their livestock and because of limited inputs in their cropping system, soil fertility mining is often observed (Kiema et al., 2014; Zougmoré et al., 2004b). Moreover, grazing areas are also under pressure as a result of agricultural land expansion due to poor yields and demographic growth (Herrmann et al., 2020; Ouedraogo et al., 2010).

Semi-arid Burkina Faso, with annual rainfall varying between 500 and 1000 mm, is a case in point of the above-described situation, with poor crop yields and livestock production, leading to food insecurity (Fraval et al., 2020; Le Garff, 2016). Crop diversification is one of the potentially affordable entry points to improve household nutrition, food security and farmers' livelihoods in sub-Saharan Africa and semi-arid Burkina Faso in particular (Waha et al., 2018). When crops with different and complementary ecological niches are associated, resource competition in space and time is limited and complete crop failure due to hazards such as irregular rainfall is minimized.

Diversification of cereal-based cropping systems with legumes has been widely proposed as a way to cope with rainfall uncertainties and combat soil fertility mining (Beillouin et al., 2020). Indeed, through the fixation of nitrogen from the atmosphere, legumes have the potential to provide additional nitrogen to the soil and thus sustain crop production. Diversification options with legumes consist of spatial and temporal arrangements of crops through cereal-legume intercropping and rotation (Falconnier et al., 2016; Franke et al., 2018). Many studies have reported the benefits of diversification with legumes on soil fertility, field productivity, pest and disease control (Alvey et al., 2001; Daryanto et al., 2020; Kermah et al., 2017). In addition, legumes represent a source of protein for households and livestock, which can improve the quality of their diet (Ajayi, 2011; Temba et al., 2016). However, while many studies investigated diversification with legumes at plot and farm level (Franke et al., 2014; Franke et al., 2018; Sanou et al., 2016), studies that uplevel the impact of crop diversification on the farming system at village level are lacking. Indeed, individual farm production depends not only on the individual management of each farm but also on interactions between farms at village level. These interactions include livestock grazing on grazing land and crop residues left in fields as well as deliberate exchange of biomass (grains, crop residues, livestock and manure) between farms. In addition, livestock mobility in and out of the village also influences the amount of manure available for cropping and thus crop yields (Berre et al., 2021). Moreover, it has been demonstrated that changes in the cropping system management (e.g. mulch) can potentially lead to trade-offs between components of the farming system, such as soils, crops, livestock, grazing areas and households (Andrieu et al., 2015; Berre et al., 2021; Rufino et al., 2011). Therefore, the present study investigated at farm and village level, the impact of diversification of a sorghum-based cropping system with cowpea and peanut, which are the most common legume crops in semi-arid Burkina Faso. The main objective of our study was to explore the impact of legume diversification on biomass production and flows, household food sufficiency and income, as well as nutrient balances and use efficiency at farm and village level in semi-arid Burkina Faso. The specific objectives were:

1. To model spatial and temporal interactions between farming system components at farm and village level.
2. To explore possible trade-offs due to crop diversification with legumes between environmental and household livelihood objectives at farm and village level.
3. To evaluate options of crop diversification with legumes on their potential to improve farmers' livelihoods and food sufficiency.

Our investigation was done using an agent-based model (ABM). We chose ABM as our modelling approach as it allows a spatially explicit representation of the study area as well as the representation of individual farms and their decision-making process. Indeed, ABMs are useful in studying spatial and social interactions in complex systems such as farming systems (Grillot et al., 2018). It is a bottom-up modelling approach, built from individual entities, such as farms, and their interactions to better understand collectives, such as the farming system of a village. In semi-arid West-Africa, ABMs have been used to investigate various aspects of farming systems, such as nutrient cycling and landscape changes (Grillot et al., 2018), carbon dynamics (Belem et al., 2011), climate variability and crop varietal diversity (Belem et al., 2018), and mulching (Berre et al., 2022). However, to the best of our knowledge, no study investigated the effects of crop diversification with legumes on biomass production and flows and the subsequent impacts on farmers' livelihoods and nutrient balance and nutrient and use efficiency at farm and village level.

As ABMs are often complex models, testing the robustness of their outputs through sensitivity analysis is key to build trust and better understand processes leading to their outputs. However, sensitivity analyses of ABMs is seldomly done in West-African studies, although highly recommended (Borgonovo et al., 2022). Furthermore, model exploration by looking at the whole range of possible outputs and associated patterns, offers opportunities to uncover the complexity of the ABM and the studied system. An example is the Pattern Space Exploration (PSE) developed by Chérel et al. (2015) to determine the possible range of outputs a model can produce. PSE is a powerful tool when it comes to studying the diversity of models' outputs allowing to further analyze synergies and trade-off between them (Raimbault and Pumain, 2023).

In our study we developed an ABM to explore the effect of crop diversification with legumes on soil, crops, livestock, grazing areas and households at farm and village level. We performed a model sensitivity analysis with all the input parameters to assess the model's robustness. Additionally, using PSE, we explored the potential of our model to analyze synergies and trade-offs between food sufficiency, income and nutrient balance and use efficiency, associated with legume diversification at farm and village level.

5.2 Materials and Methods

The sections 5.2.2, 5.2.3 and 5.2.4 describe the model theoretical framework according to the ODD (Overview, Design concepts and Details) protocol proposed by Grimm et al. (2010). The model was developed with Netlogo version 6.2.1 (Wilensky, 1999) and explored (pattern space exploration and sensitivity analysis) using the OpenMole platform (Reuillon et al., 2013). Details about the model exploration are described in sections 5.2.5.5 and 5.2.5.6.

5.2.1 Case study description

The study area is the village of Yilou (13.02°N; 1.55°W), located in semi-arid Burkina Faso, province of Bam (Figure 5.1). The village has an area of 35 km^2. The climate is characterized by one rainy season from June to October. The annual rainfall ranged from 452 mm to 1157 mm with an average of 676 mm in the 1964-2019 period. From November to February the climate is dry and cool with an average minimum temperature of 17^{o}C in December. From March to May, the climate is dry and hot with an average maximum temperature of 39^{o}C in April. Sorghum and cowpea are the most widely cultivated crops in the village. Sorghum is often intercropped with cowpea with the traditional intra-hill intercropping and crop rotation in the study area is rare (Ganeme et al., 2021). Five land uses were identified in Yilou by Dione (2020): 51% of the area is covered by agriculture, 33% bare soil, 13% woodland (considered as grazing land), 2% settlement and 1% water (Nakambe River). The village is crossed by a national road which facilitates households' access to a market and the village connection to surrounding cities. Many households of the village are engaged in gold mining which represents an important source of off-farm revenue. The farming system in Yilou is characterized by four farm types (Assogba et al., 2022) (Table 5.1), including two subsistence farm types: Subsistence-Oriented Crop (SOC) and Subsistence-Oriented Livestock (SOL) farms. The third type is the Market-Oriented and Diversified (MOD) type. This type had the largest cultivated area, a larger herd size than SOC and SOL, and half of their total revenue coming from off farm activities (e.g. commercial shops and gold mining). Lastly, the Land Constrained and Livestock (LCL) type was characterized by the smallest cultivated area, and by far the largest herd size dominated by cattle (90% of the herd). The proportions of each farm type in Yilou were 36% SOC, 32% SOL, 26% MOD and 6% LCL.

Table 5.1: Mean and standard deviation of characteristics of farm types in the study area, from Assogba et al. (2022). TLU = Tropical Livestock Unit. 1 FCFA = 0.0015 EUR. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock. Data from Assogba et al. (2022)

Variables	SOC	SOL	MOD	LCL
Household size (persons)	8 ± 4	7 ± 3	12. ± 4	15 ± 9
Herd size (TLU)	3 ± 2	3 ± 4	5 ± 4	32 ± 14
Cultivated area (ha)	2.3 ± 1.1	1.7 ± 0.9	3.6 ± 1.6	1.5 ± 0.7
Share of cultivated area rented in	0.07 ± 0.24	0.19 ± 0.36	0.03 ± 0.14	0.5 ± 0.53
Share of cattle in herd (%)	30 ± 30	20 ± 30	40 ± 30	90 ± 10
Total income (1000 FCFA)	94 ± 146	83 ± 127	957 ± 131	612 ± 497
Contribution of off-farm revenue to total income (%)	30 ± 30	20 ± 30	50 ± 30	10 ± 20

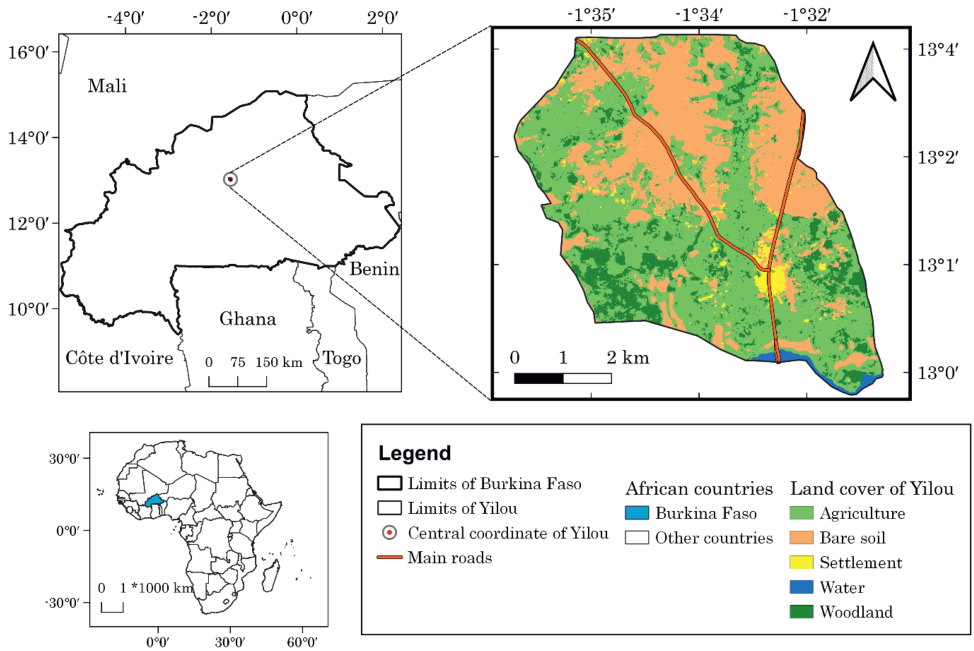


Figure 5.1: Location map of study area (Yilou) in Burkina Faso and Africa, showing the different land use types.

5.2.2 Overview of the model

5.2.2.1 Purpose

The purpose of the model is to explore the impact of resources (land and nutrients) allocation to crops on biomass production and flows, household food sufficiency and income, as well as nutrient use efficiency and balances at farm and village level in semi-arid Burkina Faso. Various model outputs for the components of the farming system (Table 5.2) were analyzed as indicators to assess the impact of plot-level crop diversification at farm and village level.

Table 5.2: model outputs (indicators) used for analysis. TLU = Tropical Livestock Unit. 1 TLU = 250 kg. 1 FCFA = 0.0015 EUR. DM = Dry Matter. N = Nitrogen. See section 5.2.5 for further details on the calculation of the outputs.

Indicators	Units	Farm level	Village level
Cropping system			
Grain yield	kg DM/ha	x	x
Crop residues produced	kg DM/TLU	x	x
Nitrogen balance	kg N/ha	x	x
Nitrogen use efficiency	kg N/kg N	x	x
Livestock system			
Herd size	TLU	x	x
Manure collected	kg DM/ha	x	x
TD (average number of days after harvest when livestock left village for transhumance)	days	x	x
TP (Proportion of livestock that left the village for transhumance)	%	x	x
Grazing areas			
Nitrogen balance	kg N/ha	x	x
Household			
Food sufficiency	%	x	x
Total income	FCFA	x	x
Gini index	-		x
FA (food received as aid)	kcal/AE	x	x
FB (food bought)	kcal/AE	x	x
RB (Crop residues bought)	kg DM/TLU	x	x

5.2.2.2 Entities, state variables and levels

Entities

The model comprises entities (i.e. agents) that interact with their environment (0). Two types of entities were included in the model: farmers and livestock. Each farmer represents a household and manages one farm, consisting of fields, crops, livestock and money. Indeed, in the model, each farmer grows crops (defined by the user of the model), harvests grain and crop residues to feed his/her household and livestock respectively. In addition, each farmer can sell and buy livestock and also manage livestock mobility across and outside the village. Farmers can earn income from crop and livestock selling as well as off-farm activities. The income is used to take care (for e.g. health care, schooling) of the household (50% of annual income) and purchase inputs (e.g. fertilizer and crop residues) for the cropping and livestock components of the farm. Farmers can exchange biomass (crop grain and residues as well as manure) with other farmers according to their needs. For example a crop-oriented farmer can exchange its surplus of crop residues with a pastoralist who will provide manure in return.

Three types of livestock were included in the model: cattle (bulls and cows), donkeys and small ruminants (representing both goats and sheep). Each of them can move, eat, reproduce, and produce manure according to its type (see section 5.2.3.1). The aggregation of all livestock belonging to a certain farm represents a herd. A herd is managed by one farmer. More details about the entities' behavior can be found in section 5.2.3.3.

Environment

The environment was based on the actual land use map of Yilou. There were five types of land use in the environment: agriculture, bush, bare soil, water and settlement. The environment was made up of plots which constitute a regular grid of 30 m * 30 m resolution (approximated to 0.1 ha). A field was made up of one or more adjacent plots. The average field area in the model was 0.4 ha (4 plots), reflecting on our field observations in Yilou (Assogba et al., 2023). Fields in the model were the closest possible to their owner settlement based on empirical observations (Assogba et al., 2023).

State variables

The class diagram presenting operations and state variables of each entity and the environment of the model is presented in Figure 5.2.

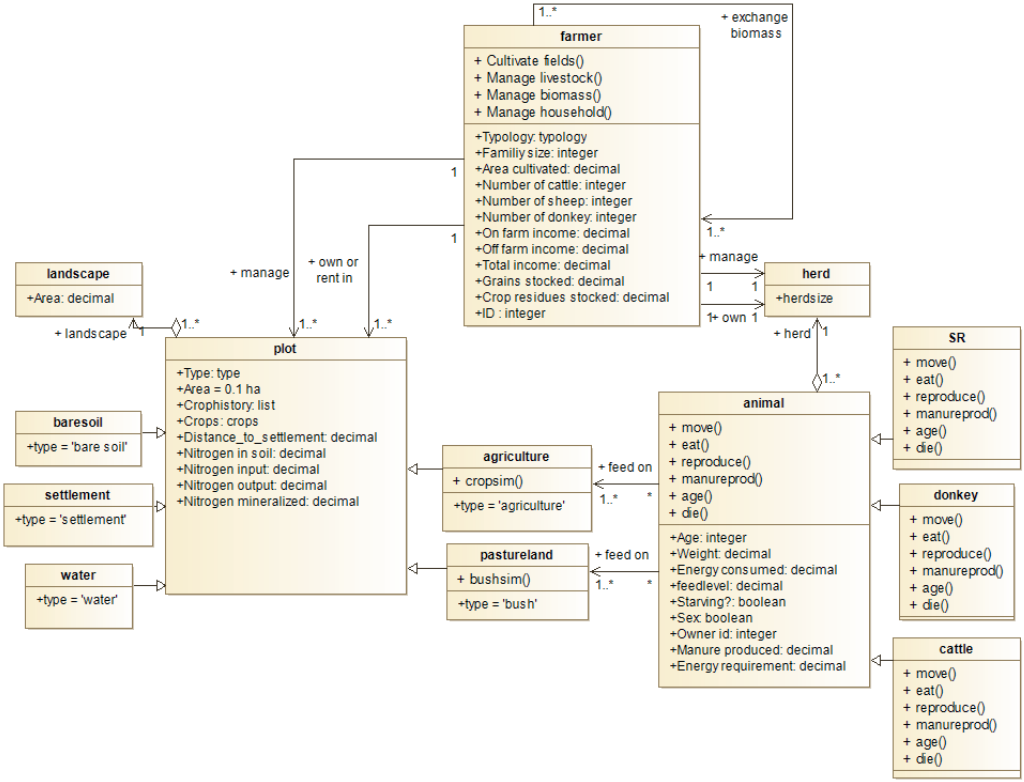


Figure 5.2: class diagram of entities and the environment of the model. SR = small ruminants. Elements of the diagram ending with double brackets "()" are operations performed by entities whereas other elements are their state variables.

Temporal level

The time step of the model is one day and indicators (e.g. nitrogen balance) were calculated on a yearly (365 days) basis. The time step of the model was set to reflect daily livestock mobility, feeding and manure production as well as farmers' decisions regarding biomass (mainly grain and crop residues) and livestock. The first step in the model corresponds to the harvest. Indeed, after initializing all state variables of the model, grain and crop residues production are computed according to rainfall and nitrogen application of each farm (see 5.2.3.1 for more details). Therefore biomass (grain, crop residues harvested and left on the soil in fields) is made available to all farms from the beginning of the simulation. It was assumed all crops are harvested at the same time.

5.2.2.3 Process overview and scheduling

The ensemble of operations taking place during a day (one time step) in the model are presented in Box 5.1 using pseudo-code.

Box 5.1: process scheduling of the model

1. If DayOfYear =1 then
    1.1. Set up (): load environment, create entities and update state variables of entities and plots
    1.2. Cropsim (): compute crop (grain and crop residues) production as well as carbon balance and nitrogen balance and use efficiency
2. Bushsim (): compute grassland production
3. Livsim (): compute livestock movement, eating, weight gain/loss, reproduction and manure production
4. Biomanag (): compute household and biomass management by farmers in the village
5. Next step: DayOfYear = DayOfYear + 1
6. If DayOfYear > 365 then
    6.1. Export (): write model's outputs into a csv file
    6.2. DayOfYear = 1
    6.3. Year = Year + 1

5.2.3 Design concepts

5.2.3.1 Basic principles

Crop and grass production

The crop grain and residue yields were calculated from multiple regressions equations derived from previously calibrated crop growth models in DSSAT (Hoogenboom et al., 2019). Sorghum (local variety CSM63E), cowpea (variety TVU3644 from Niger) and peanut (Chinese variety from Ghana) grain and crop residue yields were simulated in sole cropping for various levels of nitrogen (N) application from manure and mineral fertilizer (NPK). Amounts of N applied in the crop model ranged from 0 to 40 kg N/ha (with a 10 kg N/ha increase) for manure and mineral fertilizer each. The combination of manure and mineral fertilizer followed a full factorial design. More details concerning the crop modelling can be found in Tables S1 and S2 (Appendix 4). The simulations were run for 32 years (1990 to 2021) for which we had rainfall data from the Ouagadougou weather station (100 km away from Yilou, and similar climate zone). The outputs (grain yield, total aboveground biomass, crop nitrogen uptake and soil nitrogen mineralized) of the crop model for the different levels of N applied each year were used in a multiple regression analysis (Table 5.3). Crop residue production was calculated by subtracting the grain yield from the total aboveground biomass produced by a crop.

*Table 5.3: regressions equations giving sorghum, cowpea and peanut yield and above ground biomass production as a function of annual rainfall and nitrogen applied. Rainfall = annual rainfall in mm. Nfertilizer = amount of nitrogen applied as mineral fertilizer (kg/ha). Nmanure = amount of nitrogen applied as manure (kg/ha). N = nitrogen. The p-value of all coefficients of determination (R^2) were less than 2.2e-16. *Where: Rainfall is the annual rainfall in mm. Nmanure is the amount of N in manure applied to a field, in kg N/ha. Nfertilizer is the amount of N in mineral fertilizer applied to a field, in kg N/ha. SON is the soil organic nitrogen, in kg N/ha. Nuptake is the amount of N uptake by the crop during the growing season, in kg N/ha.*

Crop	Variable	Equations*	R^2
Sorghum	N uptake (kg N/ha)	$-0.007*Rainfall + 0.6*N_{fertilizer} + 0.5*N_{manure} + 0.005*SON$	0.99
	Grain Yield (kg/ha)	$(0.02*Rainfall + 0.6*N_{uptake})^2$	0.90
	Total aboveground biomass (kg/ha)	$(0.03*Rainfall + 1.4*N_{uptake})^2$	0.86
	N mineralized (kg N/ha)	$0.03*Rainfall + 0.6*N_{manure}$	0.98
Cowpea	N uptake (kg N/ha)	$-0.004*Rainfall + 0.5*N_{fertilizer} + 0.5*N_{manure} + 0.007*SON$	0.73
	Grain Yield (kg/ha)	$(0.01*Rainfall + 0.3*N_{uptake})^2$	0.71
	Total aboveground biomass (kg/ha)	$(0.03*Rainfall + 0.7*N_{uptake})^{2)}$	0.77
	N mineralized (kg N/ha)	$0.03*Rainfall + 0.6*N_{manure}$	0.98
Peanut	N uptake (kg N/ha)	$-0.003*Rainfall + 0.5*N_{fertilizer} + 0.5*N_{manure} + 0.006*SON$	0.99
	Grain Yield (kg/ha)	$(0.02*Rainfall + 0.5*N_{uptake})^2$	0.99
	Total aboveground biomass (kg/ha)	$(0.04*Rainfall + 0.99*N_{uptake})^2$	0.99
	N mineralized (kg N/ha)	$0.03*Rainfall + 0.6*N_{manure}$	0.98

The amount of fertilizer and manure applied by each farm depends on its income, herd size and the number of days spent by animals within the village (see 0). Each year from year two, as a simplification, N from roots of the preceding cropping season was added to N from manure in the equations of Table 5.3. The difference between N from roots and manure applied and N mineralized was added to SON. Similar N content was used for crop residues and roots. We assumed that peanut was harvested with all the root biomass. Manure was assumed to contain 1.3% of nitrogen (Sileshi et al., 2017). The N content (23%) of fertilizer (NPK) purchased in Yilou was based on direct observations from labels on the fertilizer bags.

Cereal-legume rotation was implemented in the model but the rotation effects were not explicitly investigated in this paper. However, the N input from decomposing roots of cereals and legumes of the preceding cropping season was considered. In the rotation, sorghum is grown on plots previously grown with legumes and vice versa. The plots in which sorghum and legumes are rotated were chosen randomly.

Three types of intercropping were investigated:

(1) Traditional intra-hill sorghum cowpea intercropping (SCT) in which sorghum and cowpea are sown simultaneously in the same hill. We considered that sorghum and cowpea occupied 83% and 17% of the cultivated area respectively in this intercropping type (Ganeme et al., 2021). In pure stand, sorghum rows were 80 cm apart and on each row, 40 cm separated two hills. The same spacing was respected in the traditional intra-hill intercropping. The partial and total Land Equivalent Ratio (LER) of each intercropping type are presented in Table 5.4.

(2) Strip intercropping with cowpea (SC11) which consisted of replacing half of the sorghum rows in pure stand with cowpea, so that each row of sorghum was alternated with one row of cowpea and both crops occupied half of the area. Sorghum and cowpea rows were 80 cm apart and on each row, 40 cm separated two hills.

(3) Strip intercropping with peanut (SP12) where two rows of sorghum (in pure stand) were replaced with four rows of peanut. Sorghum spacing was as above, while peanut rows were 40 cm apart and on each peanut row, 15 cm separated two hills. The area coverage of each crop was half of the pure stand.

Table 5.4: partial and total LER (Land Equivalent Ratio) of intercropping types included in the model. CR = crop residues. SCT = traditional intra-hill sorghum cowpea intercropping. SC11 = strip intercropping of sorghum with cowpea alternating one row of sorghum with one row of cowpea. SP12 = strip intercropping of sorghum with peanut replacing two rows of sorghum (in pure stand) with four rows of peanut. Data from Ganeme (2022) and Sawadogo (2021).

Intercropping type	Partial LER sorghum		Partial LER legume		Total LER	
	Grain	CR	Grain	CR	Grain	CR
SCT	0.6	0.7	0.4	0.5	1	1.2
SC11	0.4	0.5	0.6	0.6	1	1.1
SP12	0.6	0.5	0.6	0.5	1.2	1

In intercropping, grain and crop residue yields were first calculated in pure stand using equations in Table 5.3, after which the intercropped yields were obtained by multiplying the values in pure stand by the partial LER values in Table 5.4.

Grass production was derived from Breman and de Wit (1983) according to the total amount of rainfall in a given rainy season. Indeed, the annual grass production was determined by linear interpolation between 400 mm (equivalent to 1.5 t DM/ha of grass) and 1000 mm (equivalent to 4 t DM/ha of grass) of annual rainfall.

Livestock production

Livestock feed requirement (energy) was calculated from AFRC (1993) (see eq. 15, eq. 16 and eq. 17) considering that the distance walked daily by each animal was 12 km (Zampaligre and Schlecht, 2018). Daily dry matter intake (when grazing) and manure production were a function of the animal weight as found by Assouma et al. (2018). The daily dry matter intake of livestock while grazing was equal to 73 g DM/LW$^{0.75}$ (LW = Live Weight). The total daily intake of livestock is the sum of energy provided by its owner (5.2.3.3) and energy consumed when grazing. The maximum daily intake of livestock was assumed equal to their feed requirement. The daily manure production was set to 2.1 kg DM (Dry Matter)/TLU (Tropical Livestock Unit, 1 TLU = 250 kg). Livestock were assumed to spend 8.5 (cattle and donkey) and 9 hours (small ruminants) grazing per day (Zampaligre and Schlecht, 2018) and the remaining hours in the shed at home. Hence, the fraction of produced manure accumulated near the homestead was 0.62 (small ruminants) and 0.64 (cattle and donkey) (Ayantunde et al., 2001). In addition, 55% of the total N excreted in the shed was assumed to be lost due to poor manure management (Rufino et al., 2007).

Metabolizable energy requirement (MJ/day)

Cattle and donkey $$ME = \frac{0.53(W/1.08)^{0.67} + 0.037W}{k_m}$$ eq. 15

Small ruminants $$ME = \frac{0.315W^{0.75} + 0.048W}{k_m}$$ eq. 16

$$k_m = 0.35\left(ME_f/GE_f\right) + 0.503$$ eq. 17

Where: W is the weight of the animal in kg, which we assumed to be constant throughout the year. We assumed the following: 1 cattle = 0.7 TLU, 1 donkey = 0.5 TLU and 1 small ruminant = 0.1 TLU, where TLU stands for Tropical Livestock Unit and 1 TLU = 250 kg (Le Houerou and Hoste, 1977). ME is the metabolizable energy required for maintenance by the livestock in Mega Joules per day (MJ/day). k_m is the efficiency of utilization of metabolizable energy in feed by livestock. ME_f and GE_f are respectively the metabolizable energy and gross energy contents of feed in MJ/kg of dry matter. The metabolizable and gross energy content of feed were retrieved from https://www.feedipedia.org/ (accessed on 01/06/2022).

5.2.3.2 Emergence

The spatial distribution of the carbon balance, nitrogen balance and nitrogen use efficiency emerged at village level.

5.2.3.3 Agents' behavior

Biomass to feed the livestock is scarce in Yilou (Assogba et al., 2023). In the model, farmers address the lack of crop residues by purchasing the amount of crop residues required until the end of the dry season and/or by sending part of their cattle out of the village (see farmers' activity diagram, Figure 5.3). Although farmers in the model do not know the energy requirements of their animals, they judge whether the life of a particular animal is at stake based on the feed level (eq. 18) of the animal. Farmers in the model know which animals are starving and they can either purchase additional crop residues if they have sufficient income, or, if not, send the livestock out of the village (transhumance) (Figure 5.3). An animal is considered starving if for more than 10 days its feed intake is less than 40% of the energy requirement. As livestock in semi-arid West-Africa are able to cope with forage scarcity by adjusting their feed intake and body weight (Assouma et al., 2018; Ickowicz and Moulin, 2022), we assumed in the model that animals could survive with 40% of their energy requirement (Assouma et al., 2018). The amount of crop residues (harvested and purchased) provided daily to livestock was derived from biomass monitoring data (Assogba et al., 2023). If on a particular day, a farmer provides more feed than required by the livestock, they adjust the amount provided the following day by subtracting the excess of the previous day. Farmers also collect the manure excreted by their livestock near the homestead on a daily basis. When out of the village, livestock was assumed to feed only through grazing.

$$Feedlevel = \frac{Dfeed}{Feedreq} \quad \text{eq. 18}$$

Where Dfeed is the daily feed (energy) consumed by an animal in Mega Joules of Metabolizable Energy (MJ ME). Dfeed is the sum of energy provided to livestock by its owner and energy consumed when grazing. Energy consumed when grazing is 73 g DM/LW$^{0.75}$ (LW = Live Weight) (Assouma et al., 2018). Feedreq is the daily energy requirement for maintenance of an animal in MJ ME calculated based eq. 15, 16 and 17.

After harvest, livestock feed on crop residues left on the soil in fields. Animals also graze on grass available in pasture during the dry (from harvest to the onset of the rainy season) and the rainy season. Farmers in the model are assumed to know about the distribution of crop residues and grass in the village. The potential grazing area of each farmer is located in a radius of 6 km around the homestead. In the model, the potential grazing area is divided into four equal quadrants. Each farmer sends his animals for grazing on the quadrant which has on average the largest amount of biomass (crop residues and grass) available. The grazing animals are distributed over all the plots in a quadrant in such a way that the number of animals per plot is minimized. When there is no more grass available in grazing land and no more crop residues left on soil to feed on, livestock stay in the shed at home or may be send out of the village by the owner (see Figure 5.3). We assumed that female animals reproduce when for a one-year period their feed level was equal or greater than 0.8. Farmers purchase and sell livestock according to patterns observed for the farm type they belong to (Assogba et al., 2022). They sell livestock to get income and purchase grains and crop residues or more livestock to increase their herd size. Prices of items (e.g.: grains of each crop, livestock and fertilizer) are based on local observations and presented in Table S3, Appendix 4.

We assumed that farmers, after having met their household needs, sell 80% of their surplus grains each year (Figure 5.3). The remaining 20% is stocked and could be used the following years. The daily energy requirement of households was assumed at 2250 kcal per adult equivalent (FAO et al., 2001). Farmers who could not meet their households' needs with their grain production (non-food-sufficient farmers), purchase the amount of food required to meet their needs if they have sufficient income. If not, they ask for help from the four closest neighbors. This was based on the observation that some farmers who are not food sufficient can receive grains as aid from food sufficient farms (Assogba et al., 2023). Based on our observations, grain was given among related farms (from the same family) often living in the same district of a village. Hence in the model we assumed that a non-food-sufficient farm would only get help from its four closest neighbors. We assumed that neighbors with excess production would provide non-food-sufficient farms with 10% of their grain surplus in stock. For each non-food-sufficient farm, this help is received only once in a year in the simulation. The order in which non-food-sufficient farms received aid was random. If the help and/or the food purchased for a given year is not enough, farmers with less food than required are considered non-food-sufficient for the year.

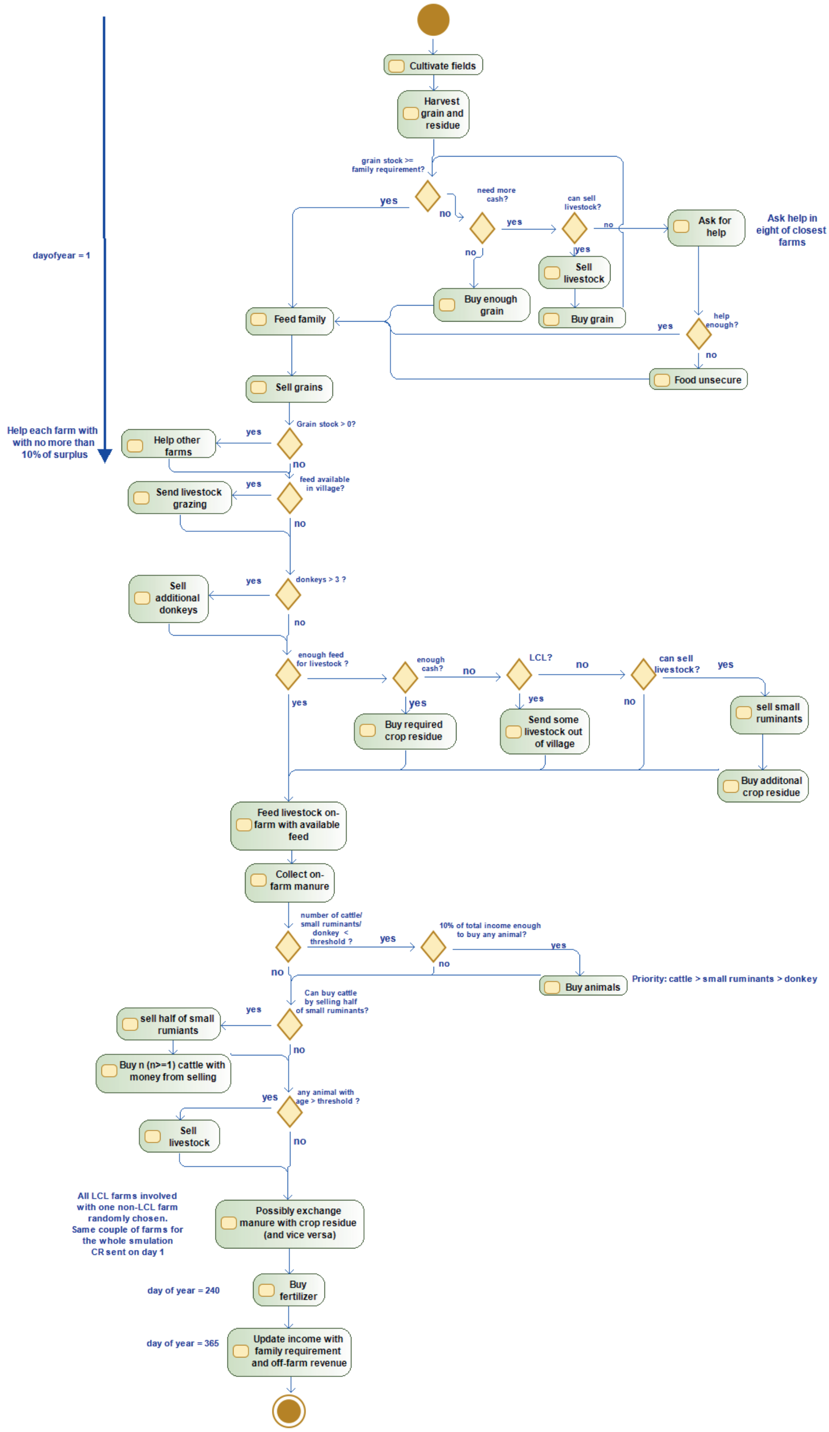


Figure 5.3: farmer's activity diagram

5.2.3.4 Objectives

Farmers' decision-making was designed to meet household needs, possibly help non-food-sufficient households (see 5.2.3.6), increase their crop and livestock production and thereby their food sufficiency and on-farm income. Concerning livestock, their objective was to meet (at least) their energy requirement (5.2.3.3).

5.2.3.5 Sensing

Farmers know the different types of land-use. They are aware of the spatial availability of crop residues, forage and manure (in grazing land) in the village. They are also aware of their neighbors and livestock grazing in the village. They can identify their livestock and fields and locate their houses. Farmers send their livestock for grazing on plots of the village that are closest to their settlement with maximum forage and/or crop residues available.

The livestock can perceive each other and the amount of forage available on the plot they are on.

5.2.3.6 Interactions

Farmers can interact directly with each other through exchange of grain (5.2.3.3), crop residues and manure. The exchange of crop residues and manure was implemented in the model but is not investigated in this paper.

Farmers in the model also interact indirectly through livestock free grazing on crop residues left on the soil in fields. Indeed, the model simulated different crop residue management options for each farm type, i.e. the fraction of crop residues produced to be harvested, used as mulch, and left on soil, was based on field observations described in (Assogba et al., 2022). Crop residues left on the soil in fields, and not meant to be used as mulch, is considered common resource in the village and can be grazed by any animal of the village.

5.2.3.7 Stochasticity

At initialization, farmers' resources (e.g. cultivated area and herd size) were generated based on typology data (Table 5.1; (Assogba et al., 2022)). For each resource, farmers were attributed a random value in the interval of the mean plus or minus the standard deviation according to their farm type. The distribution of cultivated fields was random, as to our knowledge there was no particular spatial distribution of fields in Yilou. The sex of donkeys and small ruminants (including newborns) was also random, with each sex having 50% of chance of occurrence. The same applied for cattle of large livestock owners. However, for subsistence and market-oriented farms, the sex of cattle was set to male (see section 5.2.1 for more detail on farm types) based on our observations in the farming system. The total amount of rainfall in the model was randomly chosen from an interval ranging from 450 mm to 1200 mm, based on historical data. A rainfall series of 20 consecutive years was generated and used in all simulations. The average rainfall generated was 703 mm, the minimum and maximum were 480 and 880 mm respectively.

5.2.3.8 Collectives

The aggregation of cattle, donkey and small ruminants of each farm is considered as the herd. Members of each herd grazed on the same grazing area defined by the farmer (5.2.3.3).

5.2.4 Details

5.2.4.1 Initialization

The model was set up with a village of 700 different farms in the simulation. The number of farms in the village was based on data from (Assogba et al., 2022). Based on our knowledge of the farming system, there was no particular spatial distribution of farm types, so that farms in the model were distributed randomly across the villages. All cultivated plots were assigned random nitrogen (N) and carbon (C) content values that range between the mean plus or minus the standard deviation of measured N and C content of 38 plots in the study area (Assogba et al., 2023). Manure accumulated by each farm was calculated based on their herd size. The amount of fertilizer applied by each farm type was based on data from (Assogba et al., 2022). All farms were assumed to apply all the manure they collected from their livestock.

5.2.5 Analysis

5.2.5.1 Partial nitrogen balance and nitrogen use efficiency

The partial nitrogen (N) balance and nitrogen use efficiency (NUE) were calculated for the cropping system (eq. 19 to eq. 22) at farm and village level, whereas only the N balance was calculated for the grazing land (eq. 23) at village level.

N input in the cropping system of a farm (village) was the sum of N from roots and crop residues used as mulch in the previous cropping season and N from manure and mineral fertilizer applied to all fields cultivated of the farm (village). In addition, input from biological nitrogen fixation of legumes (cowpea and peanut) was considered. A root:shoot ratio (root biomass divided by shoot biomass) of 0.3 was considered for all crops (Anderson, 1988). N content of crop residues were derived from https://www.feedipedia.org/ (accessed on 01/06/2022) by dividing their Crude Protein (CP) content by 6.25. The amount of N fixed by cowpea and peanut was estimated as 64% and 70% of the total yield (crop residues and grain) produced respectively (Phoomthaisong et al., 2003; Sanginga, 2003). N output was the sum of nitrogen in crop residues and grains harvested and grazed in all fields of a farm (village).

N inputs in grazing land included N from grass roots and shoots not grazed of the previous year and N from manure deposits from grazing animals. A root: shoot ratio of 0.3 was also considered for grass. The N output was the N contained in the total amount of grass eaten by livestock. Because biomass production in grazing land was a function of only the total rainfall, nitrogen use efficiency was not calculated for grazing land.

Equations

Farm level $$Nbal_{csf} = \frac{\sum_{i=1}^{n}(Ninput_i - Noutput_i)}{F_T}$$ eq. 19

$$NUE_{csf} = \frac{\sum_{i=1}^{n} Noutput_i}{\sum_{i=1}^{n} Ninput_i}$$ eq. 20

Village level $$Nbal_{csv} = \frac{\sum_{i=1}^{m}(Ninput_i - Noutput_i)}{V_T}$$ eq. 21

$$NUE_{csv} = \frac{\sum_{i=1}^{m} Noutput_i}{\sum_{i=1}^{m} Ninput_i}$$ eq. 22

$$Nbal_{pl} = \frac{\sum_{i=1}^{k}(Ninput_j - Noutput_j)}{P_T}$$ eq. 23

Where $Nbal_{pl}$, $Nbal_{csf}$, and $Nbal_{csv}$, are respectively the nitrogen balance of grazing land and the cropping system at farm and village level in kg/ha. NUE_{csf} and NUE_{csv} are respectively the nitrogen use efficiency at farm and village level in kg N/kg N. $Ninput_i$ and $Noutput_i$ are respectively the nitrogen input and output in the i^{th} field of a farm/village, in kg N. $Ninput_j$ and $Noutput_j$ are respectively the nitrogen input and output in the i^{th} grazing land plot of the village, in kg N. P_T, F_T and V_T are respectively the total area of grazing land, the total area cultivated by a farm and in the village, in ha. n is the total number of cultivated fields owned by a farm whereas m is the total number of cultivated fields in the village.

5.2.5.2 Household food sufficiency and income distribution

Household food sufficiency was calculated by dividing the households' energy available (from own production, purchases from the market and gifts from the neighbors) by the amount of energy required. The energy content of food was retrieved from the U.S. Department of Agriculture database (https://fdc.nal.usda.gov/index.html, accessed on 15/06/2022). Food sufficiency in the village was calculated by diving energy available in all households in the village divided by energy required by all households in the village.

Equity in income distribution of farms in the village was assessed using the Gini index (Gastwirth, 1972). The value of the index varies from zero to one with zero meaning a perfectly equal distribution of income and one meaning complete inequality (i.e. one person owns all income in the village).

5.2.5.3 Biomass production and flows

Biomass production and flows (inflow and outflow) at farm and village level were calculated. Biomass inflow at farm level included biomass purchased and biomass received as aid by a farm. Biomass outflow at farm level included biomass sold, given away and livestock death. Biomass inflow at village level included the total amount of biomass purchased by households in the village. Indeed, it was assumed that, given the context of biomass scarcity, biomass available in market came from outside the village. Also, it was assumed that all biomass sold by farmers on the market was leaving the village, so an outflow. In addition, manure lost when livestock are grazing outside of the village was also considered as an outflow.

5.2.5.4 Baseline scenario

The model was first run based on our knowledge of the current farm management practices, described in more detail in Assogba et al. (2022) and Assogba et al. (2023). Land allocation to crops per farm types is presented in Table 5.5. All farm types were assumed to grow half of their sorghum plots in intra-hill intercropping with cowpea. Manure and fertilizer were only applied to sorghum fields. No crop rotation was simulated in the baseline scenario as to our knowledge crop rotation is rarely practiced by farmers in the study area (Ganeme et al., 2021). Manure and crop residues exchange were also neglected in the baseline. Only sorghum residues were left on soil after harvest, while all legume resides were harvested. The proportion of sorghum residues left on soil was 71%, 75%, 84% and 89% for SOC, SOL, MOD and LCL farms respectively (Assogba et al., 2022). Because of stochasticity, the model was run 50 times with the same values for the input variables and the average and standard deviation of each indicator were calculated for the 20 years of the simulation and 50 model runs. We used 50 model runs in the baseline as after 50 runs there was no significant variation in the value of all indicators (5.3.1).

Table 5.5: land allocation to crops per farm type. For cowpea and peanut, the data correspond to the share of land in pure stand whereas for sorghum the share of land included intercropped (traditional intra-hill) fields. Data from Assogba et al. (2022)

Farm types	Sorghum (%)	Cowpea (%)	Peanut (%)
SOC	72	13	15
SOL	70	15	15
MOD	69	17	14
LCL	82	14	4

5.2.5.5 Sensitivity analysis

We performed a sensitivity analysis using the Morris approach (Campolongo et al., 2011). The Morris sensitivity analysis is a one factor at time (OFAT) method that assesses the impact of variation in each parameter on the model outputs. The Morris approach has the advantage to be computationally cheap while performing a robust sampling of the parameter space. The Morri eq. 24 ch calculates absolute elementary effects (Campolongo et al., 2011) which are variations of output values in response to a single variation of each parameter. In order to compare the effect of parameter variations on all outputs, the absolute proportion of change (APC) was calculated (eq. 24).

$$APC = \frac{AEE * 100}{ABV}$$

Where: APC = absolute proportion of change. AEE = average absolute value of elementary effects from varying a parameter on a given output, the average is calculated across model runs. ABV = average absolute value of the output from the baseline scenario.

We varied the value of each parameter of the model (increased and decreased) with 25% of its actual value. For a given value of a parameter, the model was run 10 times to take stochasticity into account. All parameters (except the regression coefficients of the cowpea and peanut yield regressions, Table 5.3) used in the design of the model were included in the sensitivity analysis. In total 4700 model runs were executed. The number of runs and parameters included in the sensitivity analysis were chosen as the best trade-off between computation power (and time) and accuracy of the result of the sensitivity analysis.

5.2.5.6 Pattern Space Exploration (PSE)

Description

PSE uses genetic algorithms to find the combinations of input variables leading to maximum variability in a set of target outputs (Chérel et al., 2015). In our study the input variables used were the share of land dedicated to pure stand sorghum, cowpea and peanut per farm type. In addition, we also used the share of sorghum fields that were intercropped with cowpea and/or peanut, considering the different intercropping patterns (see 5.2.3.1.).

The share of plots dedicated to sorghum was varied from 50 to 100% for each farm type during the PSE, as we assumed that a share of sorghum below 50% of cultivated plots was unrealistic. The share of sorghum plots with each type of intercropping was varied from 0 to 100%. The share of plots dedicated to cowpea and peanut in pure stand was varied from 0 to 50%. The sum of land allocated to each crop (including intercropping) always equaled 100%. As in the baseline scenario, 100% of the collected manure and fertilizer was applied to sorghum. In total 3000 runs of the model were executed with various combinations of the input variables. The number of model runs was a compromise between computation costs and the diversity of outputs that could be reached with the PSE. The PSE was run with the objective to find the maximum variability in the following outputs of the model at village level: food sufficiency, amount of food purchased per adult equivalent, herd size, amount of crop residues purchased per TLU, nitrogen balance and nitrogen use efficiency, and Gini index calculated on farm income. The average value of each output for the 20 years of each simulation was considered for analysis.

Analysis of crop diversification options

The model outputs for the 3000 runs were explored using a Principal Components Analysis (PCA) followed by a Hierarchical Clustering. The discriminating variables of the PCA were the output variables of interest, mentioned above. The input variables used in the PSE were used as supplementary variables in the PCA. The objective of the PCA and the cluster analysis was to analyze possible trade-offs between the outputs investigated at village level due to crop diversification with legumes (cowpea and peanut).

In addition, simulations leading to highest (or lowest) value of some outputs were selected for further analysis. Those were the simulations leading to values:

(1) Above quantile 99% for each of the following: food sufficiency and herd size.
(2) Above quantile 99% of nitrogen balance and below quantile 1% of nitrogen use efficiency. Nitrogen balance in the baseline was far below zero (5.3.1), so values higher than the baseline were looked for. Nitrogen use efficiency (NUE) was higher than two in the baseline, which indicates soil mining, so the combinations of input variables minimizing NUE while keeping it superior than 0.5, were looked for.

The selected simulations were ‘desirable’ simulations, i.e. the ones where farmers are food secured, the herd can remain in the territory, and N balance and N use efficiency are acceptable, as described above.

Each of the selected simulations was run 50 times, and their average outputs and input variables were used for further comparison with the baseline. In addition, the input variables of the selected simulations per farm type were analyzed in order to determine cropping systems settings of each farm type leading to the desired values.

5.3 Results

5.3.1 Baseline scenario

Simulated crop yields remained stable at farm and village level throughout the 20 years of the simulation (Figure 5.4a). Crop yields were strongly correlated to rainfall with linear correlation coefficients equaling 0.90, -0.79 and 0.81 for sorghum, cowpea and peanut respectively at village level (p-value < 0.001 in all cases). The strong dependency of yield on rainfall was mainly due to the low level of nitrogen application at field level, which was on average 13 kg N/ha considering the whole village. The amount of crop residues harvested and purchased per TLU was lowest and highest for LCL and SOC farms respectively implying that LCL farms relied the most on grazing land to feed their livestock. In addition, crop residues harvested and purchased per TLU decreased over time from the initial value by 58% and 46% for SOC and SOL farms respectively (Figure 5.4b). The decrease in crop residues harvested and purchased was due to the increase of SOC and SOL herd size (Figure 5.5a) while yields remained stable. For LCL farms, the herd size increased from 36 TLU and stabilized around 39 TLU. The herd size of MOD farms remained stable throughout years: from 6 TLU to 7 TLU. The amount of manure collected at farm level followed a similar trend as herd size except for LCL farms (Figure 5.5b). Manure collected in LCL farms was strongly and positively correlated with rainfall ($r = 0.79$, p-value < 0.001). Likewise, the number of days after harvest that the LCL herd had to leave the village (feed scarcity in the village) was positively correlated with rainfall (Figure 5.5c) ($r = 0.6$, p-value < 0.001). This implied that the higher the rainfall the later livestock left the village. These strong correlations are explained by the fact that the LCL farms get most of their feed from grazing land, where grass production was proportional to the annual rainfall. However, the proportion of animals that left, did not strongly vary during the simulations (Figure 5.5c).

The positive trend in herd size can be linked to the total income of farmers in the model. Indeed, the total income earned by all farm types except LCL farms increased over time (Figure 5.5e). The increase of income at farm level was also noticed at village level. Higher income for farmers also meant higher purchasing power (crop and livestock). For example, the amount of fertilizer applied at field level increased from 11 kg N/ha to 16 kg N/ha which explained the slightly higher sorghum yields in the last years of the simulation (Figure 5.4a). The Gini index calculated on the total income remained stable throughout the simulation and was on average 0.60 (Standard Deviation = 0.05). This suggested that the village has a strong inequality in the distribution of the total income which was owned by few farms.

Food sufficiency was always reached at the village level (108% on average) (Figure 5.5f) and was strongly correlated to rainfall ($r = 0.87$, p-value < 0.01). However, SOL farms could not reach food sufficiency, at 89% on average. At village level food purchases were necessary to reach food sufficiency with an average of 39 kg grain/AE purchased (data not shown). At farm level, with the exception of MOD farms owning the largest cultivated area, all farm types purchased additional grains. SOC farms purchased the least (14 kg/AE) whereas SOL and LCL farms with the smallest cultivated area, purchased the most (91 and 85 kg/AE resp.). Moreover, only SOC and SOL farms received on average respectively 3 and 6 kg/AE of grain as aid each year.

The nitrogen balance was always negative and gradually decreased at farm and village level throughout the years in the simulations (Figure 5.5g). However, nitrogen use efficiency remained stable at farm and village level but was always greater than one, reflecting soil fertility mining throughout the years (Figure 5.5h). The nitrogen balance in grazing land was also negative with a decreasing trend over years (Figure 5.5i). There was a strong negative correlation between rainfall and nitrogen balance in grazing land (r = -0.95, p-value < 0.001), because with higher rainfall, grass production and removal by livestock is increased, which is not compensated by more manure deposition. The latter was rather determined by livestock weight (0).

There was no particular pattern in the spatial distribution of nitrogen balance and nitrogen use efficiency at village level (Figure 5.6). Even though the modelled distribution of fields around farmers' settlement was similar to observations (Figure S1, Appendix 4), the distance between settlements and fields did not impact the spatial distribution of the nitrogen balance or the nitrogen use efficiency at village level.

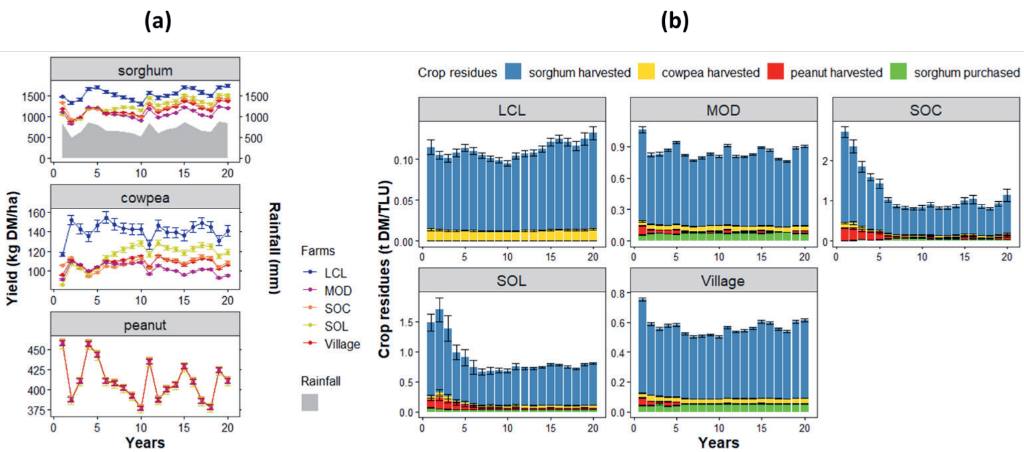


Figure 5.4: yields and crop residues harvested (and purchased) at village and farm level for the baseline scenario. DM = dry matter. TLU = tropical livestock unit. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

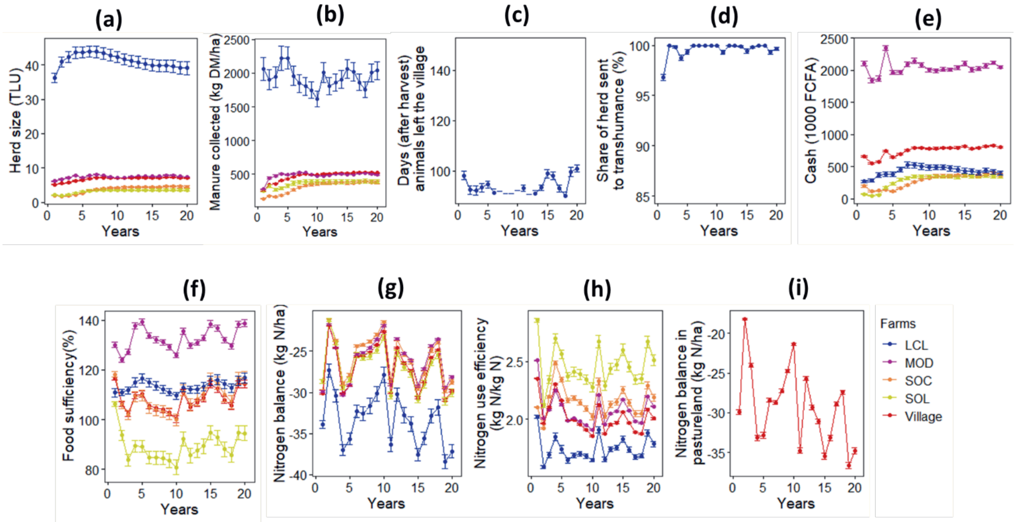


Figure 5.5: results of the model in the baseline scenario for the following outputs: Herd size (a), Manure collected (b), the day livestock left the village for transhumance (c), the proportion of livestock sent to transhumance (d), income (e), Food sufficiency (f), Nitrogen balance in the cropping system (g), Nitrogen use efficiency in the cropping system (h), and Nitrogen balance in the grazing land (i). SOC = Soil Organic Carbon. TLU = tropical livestock unit. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

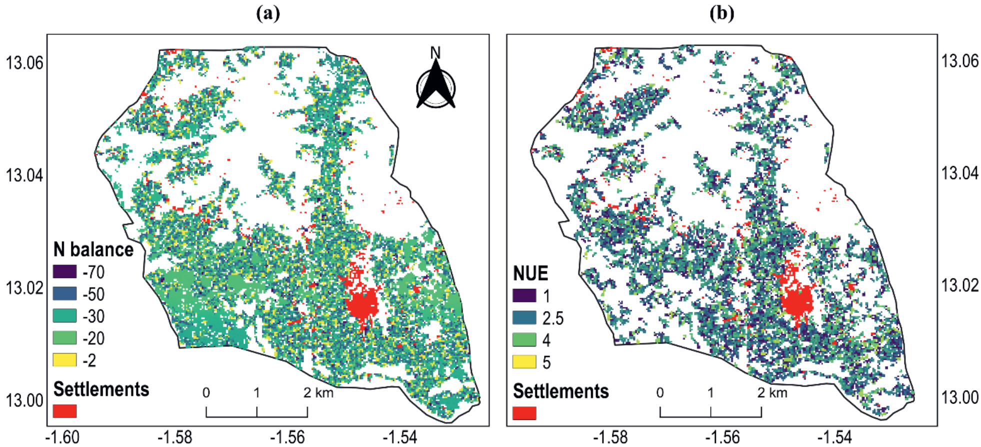


Figure 5.6: spatial distribution of nitrogen (N) balance (a) and nitrogen use efficiency (NUE) (b). The average of 20 years of simulations is shown. Note that NUE is not calculated for grazing land.

5.3.2 Sensitivity analysis

5.3.2.1 Farm level

The sensitivity analysis revealed that most of the tested parameters had limited effects on farm-level outputs (Figure 5.7a). Subsistence (SOC and SOL) farms were most affected by crop-related parameters, such as the rainfall regression coefficient in sorghum crop residue and grain yield equations and the organic nitrogen regression coefficient in the nitrogen uptake equation of sorghum. Livestock reproduction rate also had a strong influence on subsistence farms. The influence of tested parameters was more pronounced for SOC than SOL farms. LCL farms were particularly sensitive to livestock-related parameters, such as the daily feed intake and the daily feed intake threshold under which livestock were considered starving. Additionally, the reproduction threshold of livestock, the proportion of manure loss from storage as well as the amount of manure excreted daily by livestock affected mainly subsistence and LCL farms. Interestingly, MOD (market-oriented) farms were not affected by most of the parameter variations.

In subsistence farms, the most influential parameters mainly affected the total income, the herd size, the amount of manure collected, the amount of fertilizer purchased and the amount of sorghum residues stocked per TLU. Farm-level nitrogen balance was mostly affected by crop-related parameters, such as the rainfall and organic nitrogen regression coefficients in sorghum crop residues and nitrogen uptake equations respectively. Contrastingly, nitrogen use efficiency was barely affected by any parameter. Variations in the proportion of grain surplus sold by farms had a significant impact on the amount of food received as help by subsistence farms as well as their food sufficiency. The amount of food received as help was the most sensitive output regarding change in all tested parameters.

Likewise, the amount of food purchased per adult equivalent and the amount of sorghum residue stocked per TLU were the most sensitive output variables in LCL farms. Their herd size and amount of manure collected were mainly influenced by livestock feed intake and the daily feed intake threshold under which livestock were considered starving. These feed intake parameters also strongly influenced the farm-level nitrogen balance and nitrogen use efficiency. Only the livestock reproduction threshold had a slight impact in LCL farm income. Their food sufficiency was mostly affected by the proportion of grain surplus sold, and the same applied to MOD farms.

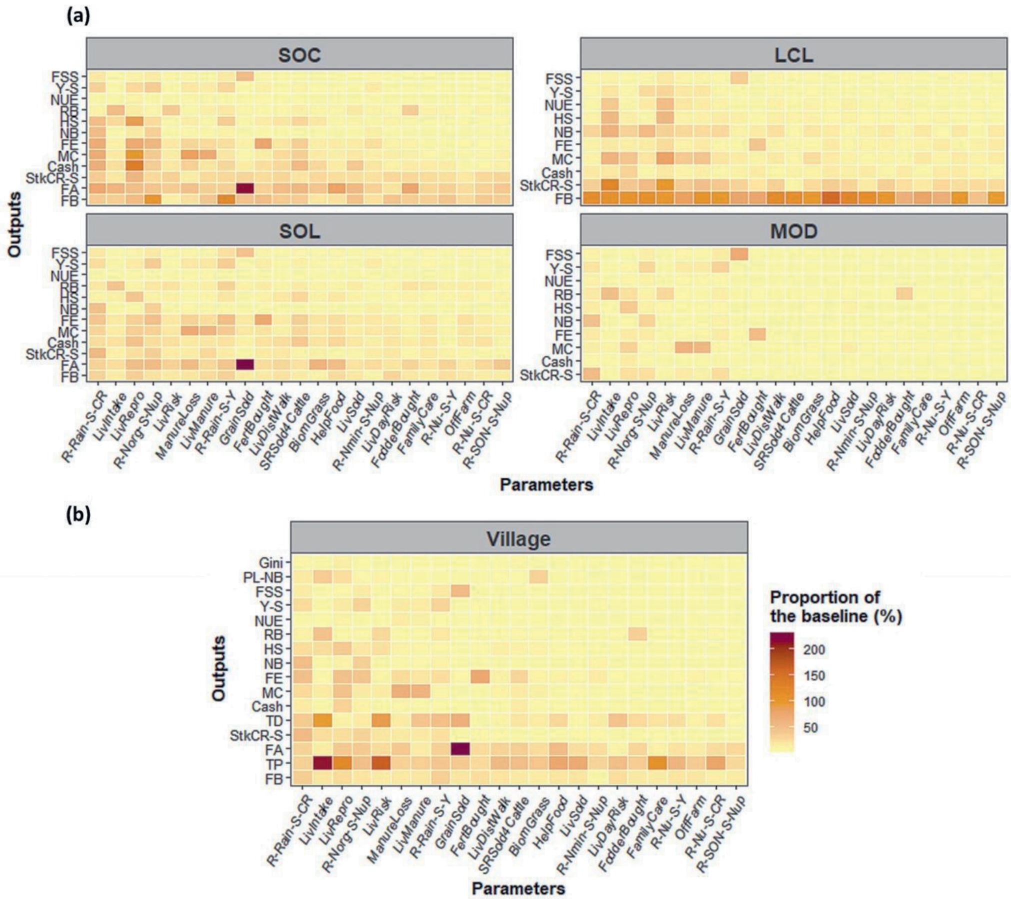


Figure 5.7: Absolute proportion of change i.e. average of Morris absolute elementary effects, expressed as a proportion of the baseline value for each output and for all tested parameters. R-RAIN-S-CR = rainfall regression coefficient in sorghum crop residues equation, LivIntake = livestock daily intake, LivRepro = reproduction threshold of livestock, R-Norg-S-Nup = organic (manure, roots) nitrogen regression coefficient in sorghum nitrogen uptake equation, LivRisk = daily feed intake threshold under which livestock were considered starving, ManureLoss = proportion of manure loss from storage, LivManure = amount of manure excreted daily by livestock, R-Rain-S-Y = rainfall regression coefficient in sorghum yield equation, GrainSold = proportion of grain surplus sold by farms, FertBought = proportion of total income used to purchase fertilizer, LivDistWalk = daily distance walked by livestock, SRSold4Catlle = proportion of small ruminants sold to purchase cattle, BiomGrass = amount of grass produced in grazing land, HelpFood = proportion of grain given away to non-food-sufficient farms, LivSold = proportion of livestock sold, R-Nmin-S-Nup = mineral nitrogen (from fertilizer) regression coefficient in nitrogen uptake equation, LivDayRisk = the number of days after which malnourished livestock was considered starving, FodderBought = amount of fodder purchased daily to feed starving animals, FamilyCare = proportion of total income used to take care (e.g. schooling, health care) of the household, R-Nu-S-Y = nitrogen uptake regression coefficient in sorghum yield equation, OffFarm = off farm income generate annually, R-Nu-S-CR = nitrogen uptake regression coefficient in sorghum crop residues equation, R-SON-S-Nup = soil organic nitrogen regression coefficient in nitrogen uptake equation of sorghum. FB = food bought, FA = food received as help, StkCR-S = sorghum residues stocked, Cash = total income, MC = manure collected, FE = fertilizer purchased, NB = nitrogen balance of the cropping system, HS = herd size, RB = sorghum residues purchased, NUE = nitrogen use efficiency of the cropping system, Y-S = sorghum yield, FSS = food sufficiency, PL-NB = grazing land nitrogen balance, TD = day livestock left the village for transhumance, TP = proportion of livestock that left the village for transhumance, Gini = Gini index. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

5.3.2.2 Village level

At village level, the most influential parameters were both crop and livestock-related parameters (Figure 5.7b, 5.3.2.1). Overall, the magnitude of the effect at village level of the most influential parameters was inferior to farm level magnitude (except for MOD farms). Village-level variations as a consequence of parameters' variations differed from the weighted average of farm level variations. For example, the weighted average of manure APC in response to variations of rainfall regression equation in sorghum yield was 21% (vs. 8% at village level). The daily livestock intake had a strong impact on the day livestock left the village for transhumance as well as the proportion of livestock that left. These outputs were also impacted by the number of days after which malnourished livestock was considered starving. The livestock reproduction threshold mainly influenced the proportion of livestock that left the village for transhumance, herd size, manure collected, total income and food received as help. As also observed at farm level, village-level food sufficiency was mostly influenced by the proportion of grains surplus sold whereas nutrient use efficiency remained unaffected by any parameter. The rainfall and the organic nitrogen coefficient in respectively the sorghum crop residues production and nutrient uptake equations affected the cropping system nitrogen balance. The grazing land nitrogen balance was only affected by livestock intake and reproduction as well as the amount of grass annually produced. The total income was barely affected by any tested parameter. The same applied to the Gini index which is also related to the total income.

5.3.3 Pattern Space Exploration (PSE)

The PCA results (Figure 5.8a) showed trade-offs associated with diversification with legumes between the model outputs. Indeed, the higher the share of land under sorghum the greater was food sufficiency, herd size in the village as well as the amount of crop residues purchased per animal. However, this was at the expense of a lower N balance and a higher N use efficiency, indicating soil mining in the village. On the opposite, increasing the share of land under sole cowpea led to relatively higher values of N balance and lower N use efficiency (i.e. less soil mining). However, food purchased to reach food sufficiency increased. The share of land under sole peanut had a positive but weak link with the first principal component, suggesting effects that were similar, though weaker, compared to the share of land dedicated to sorghum.

The trade-offs identified by the PCA were further confirmed by the hierarchical clustering that revealed three contrasted clusters of outputs of the model (Figure 5.8b and Table 5.6). The first cluster (called the sorghum cluster) had the largest share of land dedicated to sorghum as well as the highest food sufficiency and herd size. The amount of food purchased to feed households of the village was minimum in the sorghum cluster. The amount of crop residues purchased per livestock was larger than in other clusters and the N balance was the lowest. The second cluster (called the balanced cluster) had the most balanced share of land between sorghum, cowpea and peanut, with a lower level of food sufficiency than in the sorghum cluster. Nevertheless, the nitrogen balance of the balanced cluster was slightly superior to the sorghum cluster. The third cluster (called the legume cluster) was characterized by the largest land allocation to cowpea, resulting in the highest N balance and the highest income inequity. Food sufficiency and herd size were the lowest in this cluster whereas the amount of food purchased per adult equivalent was the highest.

The different types of intercropping tested were not strongly linked to the two first principal components suggesting limited impact on the output variables of the PSE. Increasing the area dedicated to strip intercropping of sorghum with cowpea would increase the N balance and the amount of food purchased as compared to pure stand of sorghum. However, food sufficiency and herd size were negatively affected. Increasing strip intercropping of sorghum and peanut had a positive but limited effect on herd size and the amount of crop residues purchased per animal. Likewise, the increase of area under traditional intra-hill intercropping of sorghum and cowpea was positively related to food sufficiency and herd size in the village. The number of years separating consecutive sorghum cultivation in a sorghum-legume rotation was not correlated with the two first axes, hence had no clear effect on the PSE outputs.

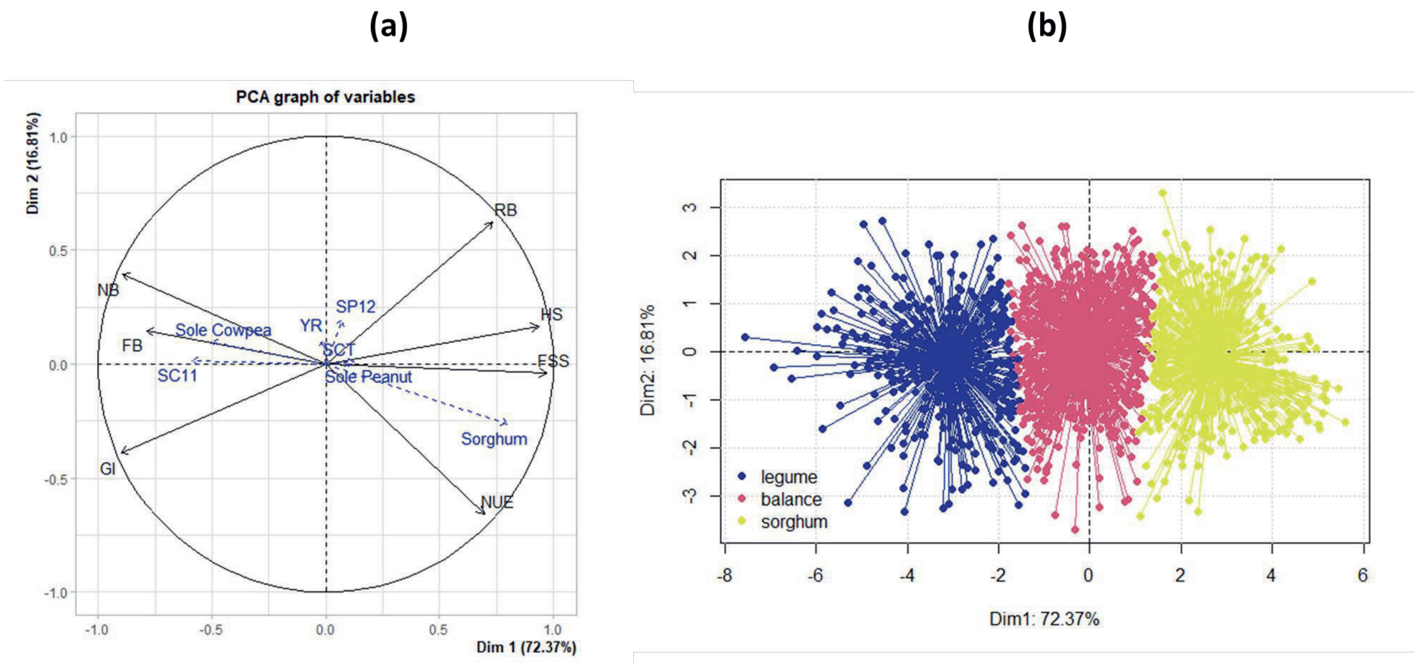


Figure 5.8 : correlation between discriminating variables (black arrows) of the Principal Components Analysis and the first and second principal components (a). Blue arrows correspond to supplementary variables projected in the correlation space between principal components and discriminating variables. Factor map showing clusters as a result of the Hierarchical Clustering on Principal Components (b). FSS = Food Sufficiency. GI = the Gini index. FB = Food bought. RB = crop residues bought per tropical livestock unit. NB = Nitrogen balance. NUE = Nitrogen Use efficiency. HS = Herd size. Sorghum, Cowpea and Peanut are the share of land allocated to each crop. SCT = traditional intra-hill sorghum cowpea intercropping. SC11 = strip intercropping of sorghum with cowpea alternating one row of sorghum with one row of cowpea. SP12 = strip intercropping of sorghum with peanut replacing two rows of sorghum (in pure stand) with four rows of peanut. YR = year separating consecutive sorghum cultivation in sorghum-cowpea/peanut rotations.

Table 5.6: mean and standard deviation of discriminating variables at the village level of three clusters of model outputs. SCT = traditional intra-hill sorghum cowpea intercropping. SC11 = strip intercropping of sorghum with cowpea alternating one row of sorghum with one row of cowpea. SP12 = strip intercropping of sorghum with peanut replacing two rows of sorghum (in pure stand) with four rows of peanut. TLU = Tropical Livestock Unit. AE = Adult equivalent. For all clusters, variables with the same letter are not significantly different.

Variables	legume	balanced	sorghum
Share of land dedicated to sorghum (%)	37 ± 4	41 ± 3b	48 ± 3
Share of land dedicated to sole cowpea (%)	25 ± 6	21 ± 5	17 ± 4
Share of land dedicated to sole peanut (%)	20 ± 6	23 ± 6	22 ± 6
Share of land dedicated to intercropped cowpea (SCT) (%)	2 ± 1	2 ± 1	2 ± 1
Share of land dedicated to intercropped cowpea (SC11) (%)	11 ± 4	7 ± 3	5 ± 3
Share of land dedicated to intercropped peanut (SP12) (%)	6 ± 3	6 ± 3	6 ± 4
Food sufficiency (%)	91 ± 3	98 ± 2	104 ± 3
Food ought (kg/AE)	90 ± 16	72 ± 9	59 ± 8
Herd size (TLU)	5 ± 0	6 ± 0	6 ± 0
Crop residues bought (kg/TLU)	40 ± 3	44 ± 3	47 ± 3
N balance (kg N/ha)	-19 ± 2	-22 ± 1	-25 ± 2
NUE	2 ± 0	2 ± 0	2 ± 0
Gini index	0.63 ± 0	0.61 ± 0	0.58 ± 0

5.3.3.1 *PSE: increased food sufficiency and herd size*

The five selected “desired” (5.2.5.6) PSE simulations with the highest food sufficiency and herd size at village level all had similar cropping systems dominated by sorghum (Figure 5.9a), occupying on average 53% of the simulated cultivated area at village level. Compared to the baseline, sole cowpea and peanut cultivation increased for all farms at the expense of sorghum and traditional intercropping of cowpea. At farm level, compared to the baseline, the share of land under sorghum cultivation was similar to the baseline except for LCL farms. Compared to the baseline, the selected LCL farms cultivated a significantly smaller proportion of their farm with sorghum which was replaced by sole peanut. Similar to the baseline, the share of land dedicated to intercropping was significantly lower than sole cropping.

The configuration of the cropping system at village and farm level in the desired PSE simulations with high food sufficiency and herd size, led to similar outputs at village level compared to the baseline (Figure 5.9c). However, the amount of food purchased to reach sufficiency was 39% superior to the baseline (Figure 5.11). At farm level food sufficiency slightly decreased from the baseline especially for LCL farms (6% decrease) possibly because part of sorghum cultivation was replaced by peanut (Figure 5.11). However, the proportion of the herd sent to transhumance as well as the day animals left the village were hardly affected. The amount of food purchased to reach sufficiency increased the most (222% increase from baseline) for LCL farms. Food received as aid slightly decreased for all farms except MOD farms which remained food sufficient. For all farm types, especially LCL farms whose cropping system became dominated by cowpea and peanut, nitrogen balance and nitrogen use efficiency in the cropping system improved by 41% and 15% respectively. This meant that negative nitrogen balance in baseline increased by 41% while nitrogen use efficiency (superior to 100% in baseline) decreased by 15%. The nitrogen balance in grazing land remained almost unchanged from the baseline.

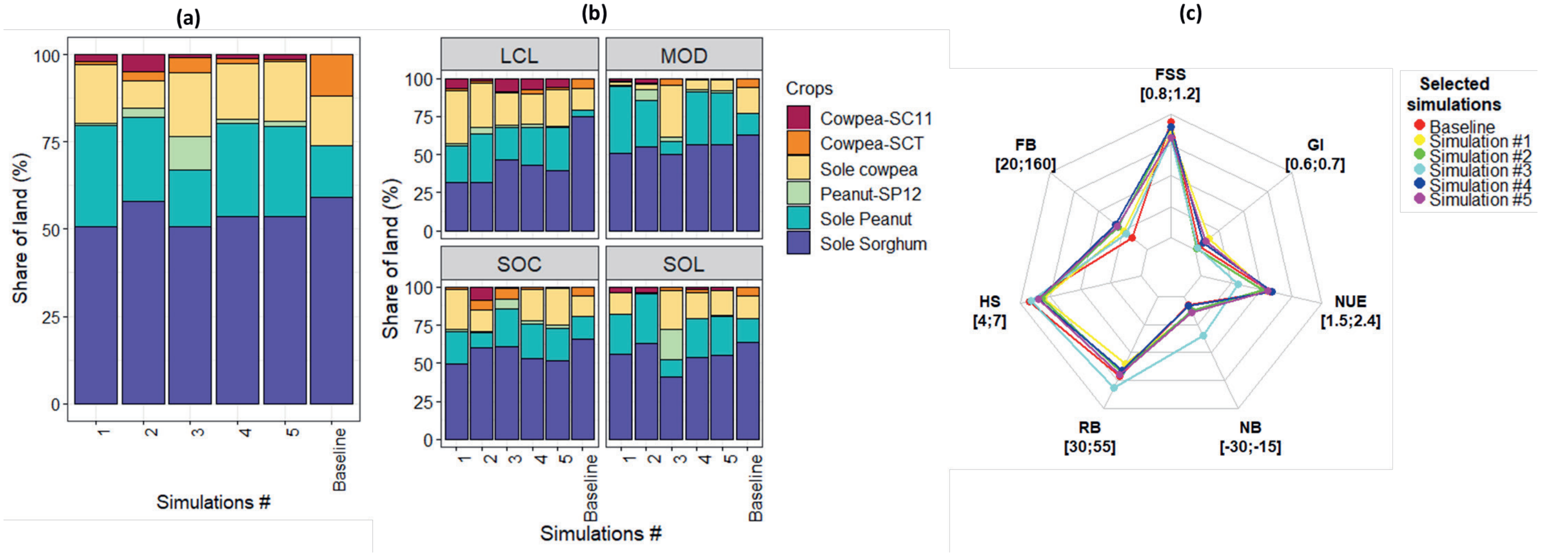


Figure 5.9 : land allocation to crops (sorghum, cowpea and peanut) leading to highest food sufficiency and herd size at village (a, d resp.) and farm level (, e resp.). Impact of simulations with highest food sufficiency and herd size on outputs of the pattern space exploration at village level (c and f resp.). FSS = food sufficiency. GI = Gini index. NUE = nitrogen use efficiency of the cropping system (kg N/ kg N). N = nitrogen balance of the cropping system (kg N/ha). R = crops residues ought (kg per tropical livestock unit). HS = herd size (tropical livestock unit). F =food ought (kg per adult equivalent). The numbers in rackets are the minimum and maximum of each outputs from the PSE and the baseline simulations. SCT = traditional intra-hill sorghum cowpea intercropping. SC11 = strip intercropping of sorghum with cowpea alternating one row of sorghum with one row of cowpea. SP12 = strip intercropping of sorghum with peanut replacing two rows of sorghum (in pure stand) with four rows of peanut. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

5.3.3.2 PSE: improving nitrogen use efficiency and nitrogen balance

The 12 selected simulations for nitrogen balance and nitrogen use efficiency met the criteria specified in section 5.2.5.6. Increasing nitrogen balance (toward zero) and reaching lower (closer to one) nitrogen use efficiency implied that legumes became the dominant crop, occupying 68% of the cultivated area in the village (Figure 5.10a). At farm level, all farm types had similar cropping system configuration dominated by sole cowpea and peanut (Figure 5.10). Additionally, strip sorghum-cowpea intercropping (SC11) had a considerable share of land. At village level, the nitrogen balance increased by 46% from the baseline but remained negative (-16 kg N/ha). Similarly, nitrogen use efficiency decreased by 22% but remained superior to one (1.5 kg N/ kg N).

Improvement of nitrogen balance and nitrogen use efficiency came at the expense of food sufficiency and the herd size. Food sufficiency was not reached at village level and equaled 87% on average. Additionally, the herd size and income in the village decreased respectively by 29% and 18% compared to the baseline. Consequently manure collected and fertilizer purchased decreased by 33% and 52% respectively. Therefore, sorghum yields were 41% lower than in the baseline. Food purchased by households strongly increased to 123 kg/AE on average. At farm level, an increase of the nitrogen balance was observed for all farm types and most strongly for LCL farms (Figure 5.11). Similar to observations at village level, the increase of the nitrogen balance was at the expense of food sufficiency and led to more food purchased for all farm types. Only MOD and LCL farms were food sufficient (113% and 104% resp.), whereas SOC and SOL farms were not (87% and 65% resp.). Food received as aid by SOC and SOL farms was reduced by 55% and 41% respectively compared to baseline because fewer farms had excess food to help their neighbors. Herd size decreased for all farm types in comparison to the baseline, especially SOC and SOL farms (66% and 40% resp.). However, the proportion of livestock sent to transhumance remained unchanged. Nevertheless the LCL herds left the village earlier as compared to the baseline. The decrease of the village herd size combined with LCL herds moving earlier for transhumance decreased the livestock pressure on grazing land which could explain that the nitrogen balance in grazing land improved (increased) by 14%. Inequality in income distribution slightly increased (7%) from the baseline as a result of the significant decrease of farm income, especially in subsistence farms.

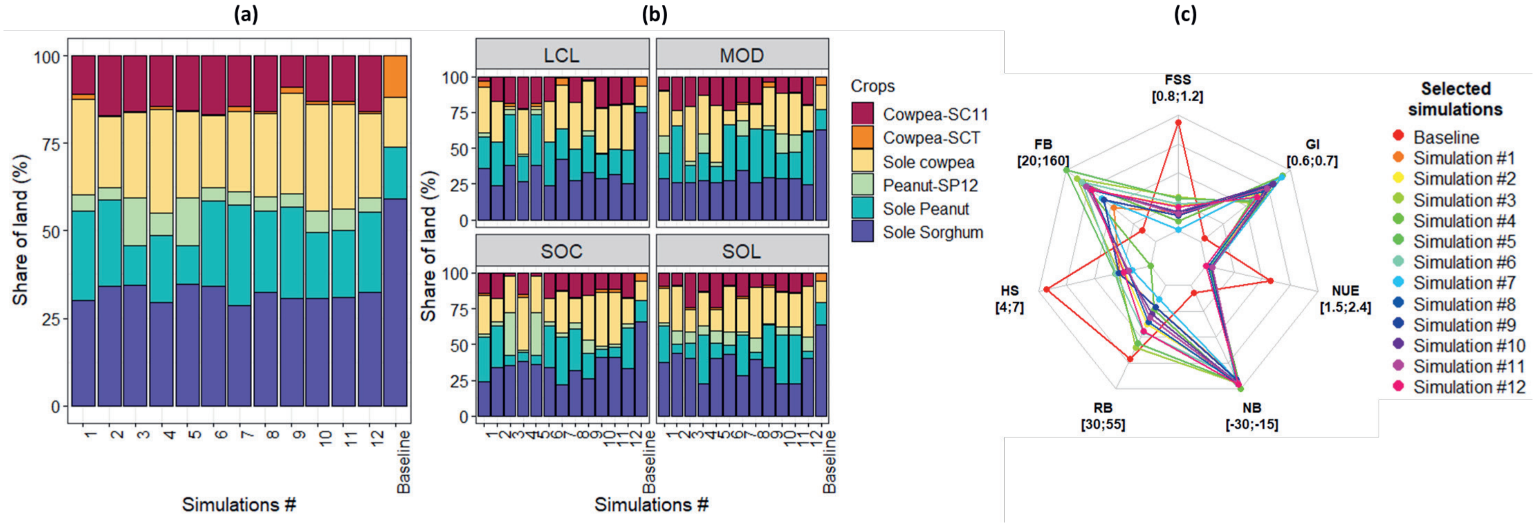


Figure 5.10 : land allocation to crops (sorghum, cowpea and peanut) leading to lowest nutrient use efficiency and highest nitrogen balance at village and farm level (a, b resp.). Impact of simulations with lowest nutrient use efficiency and highest nitrogen balance on outputs of the pattern space exploration at village level (c). FSS = food sufficiency. GI = Gini index. NUE = nitrogen use efficiency (kg N/ kg N). N = nitrogen balance (kg N/ha). R = crops residues ought (kg per tropical livestock unit). HS = herd size (tropical livestock unit). F =food ought (kg per adult equivalent). The numbers in rackets are the minimum and maximum of each outputs from the PSE and the baseline simulations. SCT = traditional intra-hill sorghum cowpea intercropping. SC11 = strip intercropping of sorghum with cowpea alternating one row of sorghum with one row of cowpea. SP12 = strip intercropping of sorghum with peanut replacing two rows of sorghum (in pure stand) with four rows of peanut. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

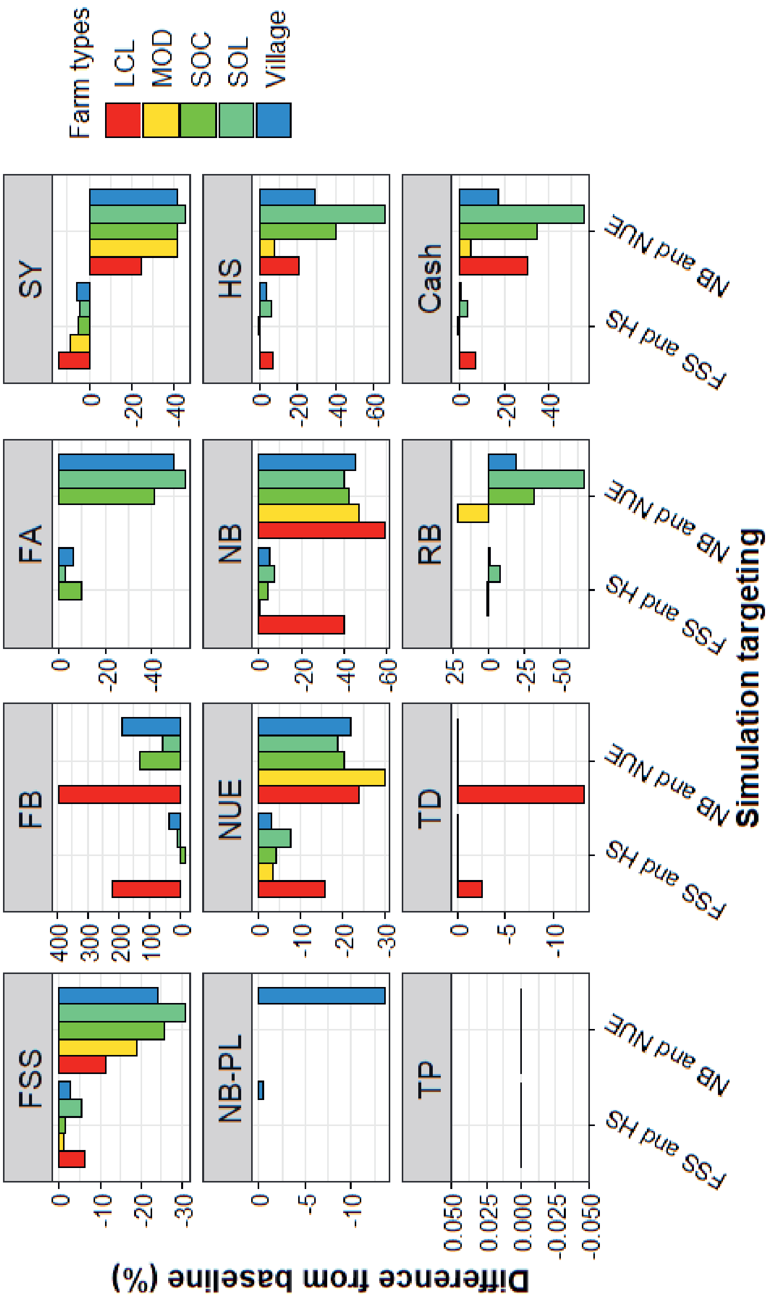


Figure 5.11: Impact of selected simulations from the Pattern Space Exploration (PSE) on indicators of the farming system. FSS = food sufficiency, FB = food bought, FA = Food received as aid, SY = sorghum yield, NB-PL = nitrogen balance in grazing land, NUE = nitrogen use efficiency in the cropping system, NB = nitrogen balance in the cropping system, HS = herd size, TP = proportion of herd sent to transhumance, TD = day last animals left the village for transhumance, RB = crop residues bought, and Cash = total income. LCL = land constrained livestock, MOD = market-oriented and diversified, SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock.

5.4 Discussion

We developed an agent-based model to explore nutrient cycling, biomass flows and famers' livelihoods in mixed crop-livestock farming systems of West-Africa. In section 5.4.1, we evaluate the model outputs regarding findings from literature and explain the processes behind the model's results. Additionally we analyze the sensitivity of the model to its parameters at farm and village level in section 5.4.2. In section 5.4.3 we discuss the impact of crop diversification at farm and village level and the implications of the model results for agriculture in the area. Finally section 5.4.4 presents the limits of the study as well as future improvement and use of the model.

5.4.1 Model performance and simulated patterns

In the baseline scenario, simulations produced relatively stable yields, clearly related to rainfall. This was not surprising as rainfall was part of the regression equations used to calculate yields and reinforced due to the low level of fertilizer application. The correlation between rainfall and crop yields in Burkina Faso was recently shown also by an empirical study by Sanou et al. (2023). Our simulations also revealed negative N balances in the cropping system for all farm types and at village level. This is in line with the results of Diarisso et al. (2015) and Grillot et al. (2018a) who also found negative N balance in the cropping system respectively at farm and village level in mixed farming systems of semi-arid West-Africa using an empirical and agent-based modelling approach respectively. NUE was always greater than one, implying N mining because of larger N export than N inputs. For grazing land, the negative N balance was caused by the fact that N inputs from livestock dung could not compensate the N removal due to grazing. A similar result was found in ABM studies by Andrieu et al. (2015) and Grillot et al. (2018a) in grazing areas of semi-arid West-Africa. We found no spatial pattern in N balance and NUE in the village. This could be explained by (1) the spatial configuration of the settlements in the village which was a mix of big and small settlement groups, (2) grazing areas were scattered over the village and (3) in the model we did not include distribution of manure according to distance between fields and farmers' settlements as this was not observed in the village (Assogba et al., 2023; Diarisso et al., 2016).

In the model, the simulated herd size increased, from the initial values, especially for subsistence farms that represented 68% of farms in the village. However, all herd sizes stabilized five to ten years after the start of the simulation when an equilibrium is reached between the feed resources (crop residues and forage from grazing land) and livestock requirements. This initial increase can be explained the mechanisms and input parameters implemented in the model, especially for livestock feeding, reproduction and mobility, leading to higher herd size than the initial value (see 5.4.2). In addition, our model constrained livestock to feeding in the village first before eventually leaving for transhumance because of lack of feed in grazing land. In reality, livestock could stay longer in the village, grazing in surrounding villages and coming back to their owner every now and then. The difference between the real-life and modelled grazing behavior explained why agro-pastoralists herd moved out of the village earlier than reported (Assogba et al., 2023).

At village level, food sufficiency was always reached even though it required additional purchase of grains. However, at farm level, not all farms were food sufficient despite food received as help from households with food surpluses. Indeed, 11% of subsistence farms were not food sufficient and did not have enough income to purchase additional grains. Fraval et al. (2020) also found similar results concerning food sufficiency in semi-arid Burkina Faso. The total income distribution among farm types did not change throughout years but had a similar trend with herd size. Both total income and herd size could have influenced each other reciprocally, as an increase of herd size also implied potentially more income from livestock selling, and that income could be used to purchase additional feed or young animals in the model.

5.4.2 Sensitivity of farm and village indicators to model input parameters

The sensitivity analysis revealed that village level indicators were sensitive to both crop and livestock-related parameters, such as were rainfall and nitrogen in crop production and livestock intake, reproduction and starvation threshold. These parameters affected the village and farm level differently and village level results differed from a simple extrapolation or weighted average of farm level results (Grillot et al., 2018a). This pointed out the importance and added value of using an ABM as it includes interacting individual farms allowing multiple-level analysis of regressive, additive or synergy effects in a farming system (Bert et al., 2011; Marvuglia et al., 2022). In our study, for most parameters a regressive effect (i.e. a reduction in the proportion of change from the baseline) was noticed when moving from farm to village level, possibly due to the non-uniform distribution of the impacts of tested parameters at farm level.

Actually, the sensitivity analysis also reflected that tested parameters affected each farm type differently. Subsistence farms were more affected by crop-related parameters, mainly rainfall and nitrogen in crop production, which are considered as the main limiting factors for crop production in the area (Diarisso et al., 2016; Sanou et al., 2023). As subsistence farms invested a limited amount of nitrogen on a relatively small piece of land, the crop response to rainfall and nitrogen strongly affected their food availability. Indeed, they have the lowest income and the smallest herd size, so their possibilities to handle variations in crop production by selling livestock to purchase additional grains are rather limited. On the opposite, the market-oriented and diversified farms were barely affected by variations in any parameter. This is probably due to them having by far the highest income and half of it coming from off-farm activities, allowing them to better cope with changes in their farm systems compared to subsistence and agro-pastoralists (LCL). The latter, owning by far the largest herd size but cultivating on the smallest areas, were more affected by livestock-related parameters. Contrary to subsistence farms, they applied considerable amounts of manure in their cropping system and get their income mainly from livestock selling. The latter can also be used as a coping strategy to get income to purchase additional grains and remain food sufficient. As agro-pastoralists relied mainly on grazing land to feed their livestock, variation in the daily feed intake value in the model determined whether and when their herds would leave the village. Likewise, the livestock reproduction threshold influenced how the herd size varied according to the livestock feed level. The threshold was fixed arbitrary in the model, so a more accurate representation of reproduction conditions could improve the model. This will require additional studies to compensate data scarcity in pastoralist and agro-pastoralist livestock production systems in semi-arid West-Africa.

5.4.3 Crop diversification impacts at farm and village level

With the currently low nitrogen application rates, it was not possible to maximize food sufficiency and herd size while minimizing soil fertility mining and the purchase of grain and crop residues. Crop diversification with legumes would most likely improve the N balance of the cropping system at farm and village level. However, food sufficiency was only maintained if sorghum remained the main crop in terms of land allocation. This was particularly observed for subsistence farms which could not compensate for grain and crop residues loss due to the replacement of sorghum by legumes. On the opposite, non-subsistence farms could maintain food sufficiency only by purchasing food on the market. Similar results were found at farm level by Franke et al. (2014) in the case of no additional nutrient application to legumes. However, these authors demonstrated that when reducing the share of land allocated to maize, the eventual grain loss can be compensated with adequate fertilization on legumes with phosphorus (P). Likewise, Kiwia et al. (2019) demonstrated that appropriate fertilization in cereal-legume intercropping is needed to guarantee superior profit compared to sole cropping. Our results also confirmed that, even if legumes have similar (peanut), or higher prices (cowpea) than sorghum, the limited amount of grain produced with little fertilizer and/or manure did not lead to higher economic benefits than the current practice at farm and village level.

Additionally, the contribution of legumes to the farm system differed between cowpea and peanut. Indeed, with the current cropping system management, cowpea was more effective at alleviating soil fertility mining while peanut seemed a good compromise between N balance improvement and grain and residue loss. A similar result was found by (Snapp and Silim, 2002) while evaluating trade-offs between productivity and soil fertility related to diversification with legumes in Malawi and Kenya. This points out that diversification with legumes should include crops with different advantages in term of productivity, soil fertility and profit especially in mixed crop-livestock systems. Indeed, the entry-points to improve the production of the diversity of farms are different (Assogba et al., 2022). Therefore, the most suitable diversification option may differ according to the farm orientation toward crop or livestock, and their production goals (subsistence or market).

Scaling up crop diversification from plot level to village level demonstrated the importance of the interactions between farms as well as the feedbacks between components of the farming system. Our model results suggested that targeting alleviation of soil fertility mining would decrease the herd size and farm income, hence manure and fertilizer applied and thereby crop yields. The magnitude of these negative impacts varied from farm to village level. Indeed the adverse effects of diversification with legumes can be moderate (herd size and income) at village level, while at farm level subsistence farms were more often severely affected (Figure 5.11). In addition, food sufficiency of subsistence farms depended to some extent on grains received as help from other farm types. However, higher share of land dedicated to legumes was at the expense of the total grains produced at the village level, which limited the amount of grain received by subsistence farms to improve their food sufficiency. Moreover, given that legumes residues are usually completely harvested by farmers, increasing the share of land under legumes also implied less crop residues from sorghum available for grazing to all. Similar results were found by (Andrieu et al., 2015) and (Berre et al., 2021) when investigating respectively private crop residue use and mulching at village level in Burkina Faso. The reduction of herd size and income resulting from crop diversification had a negative feedback on the farming system as it increased biomass scarcity and would reduce possibilities of simultaneously feeding the soil and feeding livestock in mixed crop-livestock systems. However, in the long term, the current cropping system management could also lead to the same situation because of the continuously declining soil fertility in cropland and grazing land. Currently farmers seems to be targeting short-term food sufficiency at the expense of soil fertility with strong dependence on grazing land to feed their livestock. Therefore, higher nutrient inputs (Falconnier et al., 2023) combined with crop diversification might be an option to guarantee long-term food sufficiency.

5.4.4 Further improvement and use of the model

The range of model outputs discovered in this study was a function of the number of runs included in the PSE. The higher the number of runs, the higher is the possibility to discover new pattern in the model output (Chérel et al., 2015). As our objective was to explore the diversity of model outputs regarding crop diversification and associated trade-offs, the optimal cropping system for various targets such as food sufficiency may be different from the ones described. Other optimization algorithms such as NSG2A (Deb et al., 2002) will be more useful to specifically determine the optimal cropping systems configuration for a given targeted output such as food sufficiency or nitrogen balance.

In the current version of the model, farmers' decision-making has little flexibility. Their decision-making was based on mechanistic rules rather than behavior theories (Speelman, 2014). More flexible decision-making can help studying further the impact of social interactions and organizations on the farming system of the model. A possible development of the model could also include demographic growth and its effects on land use. This would require more than 20 years of simulations. In addition, labor requirement for cropping activities and livestock keeping is completely absent from the model. The availability of labor is a major factor affecting whether a certain innovation can be adopted or not (Arslan et al., 2022).

We currently only considered energy in food available for households to define their food sufficiency status. Further improvement of the model could also consider protein and other nutrient requirements. Additionally, food ration that consider farmers' food preferences can lead to more realistic scenarios. Moreover, we only looked at diversification from a production and environmental point of view. Other potential effects in terms of, for example, pest and disease control (Daryanto et al., 2020) and the reduction of striga infestation in monoculture of sorghum (Khan et al., 2007) were not considered.

Further use of the model can explore crop diversification with legumes in combination with higher fertilization rates, especially for legumes. Moreover, the model can be used to further investigate possibilities of better crop-livestock integration at village level through exchange of livestock, manure and crop residues in various scenarios.

5.5 Conclusion

We developed an agent-based model to simulate and explore biomass production and flows, nitrogen balance and nitrogen use efficiency as well as farmers livelihoods at farm and village level. With the current farm management, the model revealed soil fertility mining at farm and village level. In addition, food sufficiency was always reached at village level but at farm level, subsistence farms with limited herd size, cultivated area and income could not always reach food sufficiency. These subsistence farms remained non-food-sufficient even with grain received as aid from neighbors with excess of production regarding their households' requirements. Our study revealed the importance of a bottom-up approach, such as ABM, to study farming systems at various levels. Indeed, we showed that village level results were not an aggregation of results from farm level but also depend on interactions between farms. Mainly the annual rainfall, nitrogen availability to crops, livestock feed intake and reproduction influenced the results of the model and these influences varied from village to farm level as well as across farm types.

Our study demonstrated that, with the current level of nutrient application, room to increase both food sufficiency and herd size while improving nitrogen balance and use efficiency is limited. In addition we showed that the current farm management was targeting food sufficiency and herd size at the expense of soil fertility mining. We discussed that higher fertilization rates would be needed to alleviate soil fertility mining with legumes while maintaining food sufficiency on the long term.

5.6 Acknowledgements

We thank the McKnight foundation which funded this research through the 3F (Feed the soil and Feed the livestock to Feed the people) project. We also thank the CUOMO foundation for providing additional scholarship. Finally we thank farmers, agronomists and researchers from Burkina Faso who helped us collect the data that form the basis of this work.

6 General discussion

6.1 Introduction

Improving crop-livestock integration and production in sub-Saharan Africa (SSA) offers opportunity to improve food security and nutrient recycling (Rufino, 2008). In my thesis, I investigated, in semi-arid Burkina Faso, a farming system dominated by farmers combining crop and livestock production to make a living. However, crop-livestock production remains extensive and a significant proportion of farms are still food insecure (Fraval et al., 2020). Therefore, the main research objective of the thesis is to explore how to improve crop-livestock integration and production in West-Africa to improve food security with a particular focus on semi-arid Burkina Faso. This research question was translated into four objectives:

1. To identify key levers to improve biomass management in semi-arid Burkina Faso (chapter 2).
2. To assess the extent to which current farm management is able to sustain crop and livestock production and fulfil household food requirements (chapter 3).
3. To better understand farmers' decision-making and explore mixed farm systems for stronger crop-livestock integration and better production (chapter 4).
4. To explore the impact of legume diversification on biomass production and flows, households' food self-sufficiency and income, as well as nutrient balances and use efficiency at farm and village level in semi-arid Burkina Faso (chapter 5).

To address my research objective, participatory research with a system approach was applied. Both qualitative and quantitative methods were combined to account for social and biophysical dimensions of the farming system. Additionally, the farming system was investigated at plot, farm and village level considering interactions and feedbacks across levels. The overall approach was based on the DEED (Describe, Explain, Explore and Design) cycle (Descheemaeker et al., 2019; Giller et al., 2011). However, my methodological approach focused on the Describe, Explain and Explore phase of the cycle. I first collected extensive data on all components of the farming system to better understand its current state (Describe and Explain, chapters 2&3). These data were integrated in exploration tools (models, chapters 4&5) in order to find relevant options considering farmers' constraints (e.g. labor) and the complexity of the farming system. In this chapter, the novelty of the results and the methodological approach are highlighted. The strength and limitations of methods are also discussed. Finally, I propose a new framework for co-design of new farming systems with farmers.

6.2 Multi-level understanding of biomass production and management in mixed crop-livestock farming systems

6.2.1 Main findings for farming system of semi-arid Burkina Faso

Mixed crop-livestock farms in SSA are known to be characterized by extensive production with poor nutrient recycling (Powell et al., 2004; Rufino, 2008). My research confirmed that mixed crop-livestock farms in semi-arid Burkina Faso are in a vicious cycle rather than a virtuous one (chapters 2 and 3) (Figure 6.1). This was valid for plot, farm and village levels. Actually, potential synergies offered by crop-livestock integration such as nutrient recycling at farm level were barely exploited because of significant yield and feed gap in the cropping and the livestock system respectively. At village level, synergies between crop and livestock oriented farms remained limited because of poor farm level crop and livestock production. Consequently, the impact of farms interactions at village level on crop and livestock production at farm level was negligible.

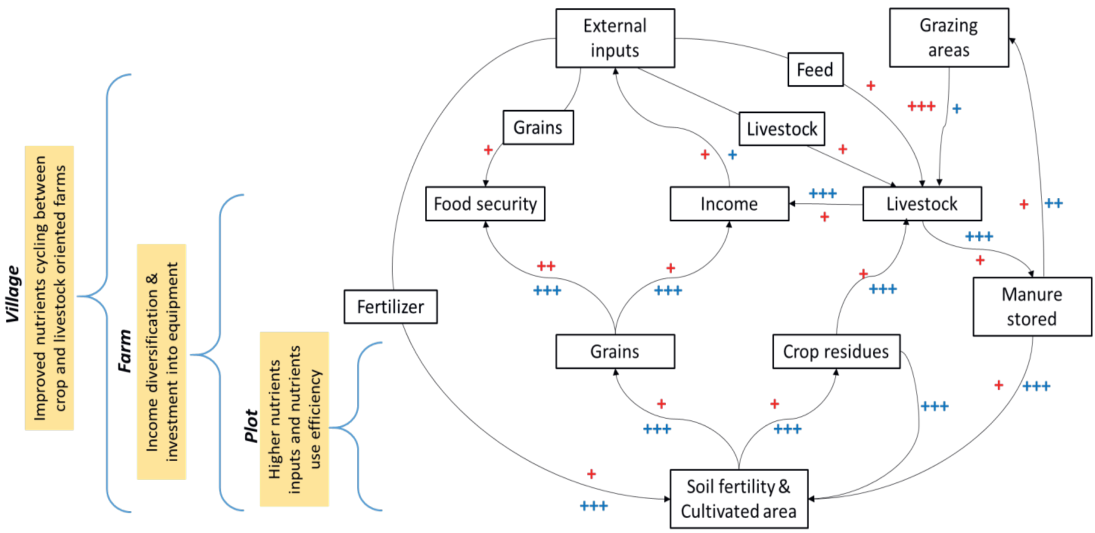


Figure 6.1: schematic representation of current (red signs) vs. more integrated (blue signs) mixed farm system. The number of "+" represents the intensity of relations between components of the system. Orange boxes are potential levers for better crop-livestock integration and production.

Overall, biomass production and management were driven by two factors: the total cultivated area and the herd size. The total cultivated area determined the amount of crop residues produced, hence inflows at farm level. Additionally, the herd size determined the proportion of crop residues harvested, left on fields (both eaten by livestock), and sold. For example, subsistence farms with the smallest herd size were the only one to sell their crop residues. Moreover, the higher the herd size, the higher was the total amount of crop residues and/or concentrate feed to feed the livestock. However, per unit of livestock the opposite was observed meaning that the amount of complementary feed purchased by unit of livestock was higher for farms with relatively small herd size. Consequently, farms with relatively higher herd size were the most dependent both from complementary feed purchased but also forage inflows from grazing land. Actually the whole farming system (village level) was highly dependent on external inputs, especially to feed its livestock component. Livestock mobility outside of the village in search for forage represented a source of nutrients (manure) loss that would have been otherwise available for crop production.

I demonstrated that nutrient recycling in the farming system is negligible leading to soil fertility mining at plot level (chapter 3). Our results confirmed a previous study by Diarisso et al. (2016) who also demonstrated soil fertility mining in addition to important yield gaps linked to insufficient organic and mineral nutrient inputs in the cropping system. I found three main sources of nitrogen differing by their order of magnitude in the cropping system: first, nitrogen coming from legumes, followed by the one coming from manure and to a lesser extent, the one coming from mineral fertilizer. The nitrogen input from legumes was insufficient to offset the negative nitrogen balance in the cropping system, because legume crops (cowpea) typically occupy a small proportion of land in intercropping with sorghum. I also showed that manure application was proportional to the herd size but manure was poorly handled by farmers, stored in uncovered and unroofed piles, leading to poor manure quality with little nitrogen content. Rufino et al. (2007) demonstrated that this poor manure management leads to considerable nitrogen loss through volatilization and leaching. Fertilizer was barely applied by farmers probably because of limited financial capital. Crop residues used as mulch could represent another potential source of nutrients in the cropping system. However, we demonstrated that livestock pressure on the cropping system left no room for mulching as fencing was too costly. Farmers harvested crop residues to feed their livestock at home and the remaining crop residues left on the soil were eaten by the livestock herds in the village grazing freely (chapter 2). This suggested that the current crop residue management in the village benefits farms with relatively larger herd size at the expense of the subsistence farms with smaller herd size (Andrieu et al., 2015; Rufino et al., 2011).

I quantified livestock feed gap throughout a year and across farm types (chapter 3). This information fills an important knowledge gap for mixed farming systems in semi-arid West-Africa (Assouma et al., 2018). Overall, there was a large gap between livestock feed requirement and feed provided by farmers. In fact, even though farmers complemented their feed production with concentrate feed (cotton seedcake and sorghum bran) and Piliostigma (*Piliostigma reticulatum* DC. Hochst) pods, the amount of feed available was still not enough to feed the livestock. Livestock relied on grazing land and crop residues left in the fields during the first weeks after harvest as well as during the rainy season. While agro-pastoralists, with the largest herd size, left the village for months between the end of the dry season and harvest, other farms sent their livestock away for days up to weeks in search for forage in the surrounding villages. I concluded that even though the cropping system cannot feed the livestock, farmers still prefer to keep as much livestock as they can, relying on village grazing areas, even if they are highly unproductive (Otte and Chilonda, 2002). Indeed, livestock production and reproduction performances are not the only reason why farmers keep livestock in semi-arid Burkina Faso. Other factors enter into considerations such as the social status and the use of animals for farming operations (ploughing, threshing, and transport) (Molina-Flores et al., 2020; Moll, 2005) and risk management (Huet et al., 2020).

Interactions between farms at village level were also quantified and explored in this thesis (chapters 2 and 3). In addition to grazing on crop residues, farms interacted directly through manure left on grazing land. A significant share (65% on average) of applied manure of non-agro-pastoralists farms came from manure mainly left by agro-pastoralists herds in grazing land (chapter 2). Manure being collected in grazing land is an indicator of biomass scarcity and farmers trying their best to maintain or even increase their production with their limited resources. In fact, as nutrients inputs in the cropping system were limited, farmers made use of all resources they have access to in their farms and within the village for improving their crop production. Exchange of harvested crop residues and manure was also reported in addition to grain given away in solidarity to non-self-sufficient farms. However, because of pressure on crop residues harvested this type of exchange is rare. Interactions between farms revealed potential complementarity between them depending on their orientation towards crop or livestock production. However, given the limited amount of grains and crop residues produced by the cropping system, there is currently little room to foster the interactions (chapter 2).

My results confirmed the importance of multiple level analysis of the farming systems. I showed that biomass production in mixed crop-livestock systems was dependent on the biomass management of individual farms as well as direct and indirect interactions between farms in the village (Figure 6.1). Actually, livestock in the farming system put a high pressure on crop residues produced (farm level) and forage in grazing land (village level) which was poorly recycled in fields as manure applied to the fields (plot level). Despite significant inflows of manure from grazing land to the fields, crop and livestock production remained poor. Manure was key for plot level crop production as it was the first and the main source of nitrogen directly applied by farmers. Manure accumulated in farms was also dependent on livestock mobility outside the village which was driven by fodder production in farms and forage availability in the village. Hence, crop and livestock production were the result of plot and farm level biomass management as well as biomass availability within and outside the village. I showed that interactions within and across levels allowed a better understanding of the farming system functioning which is the first step toward exploration of relevant options to improve crop-livestock integration and production.

6.2.2 Challenges and opportunities for improved crop-livestock integration and production

Potential levers for more integrated crop-livestock systems come from within and outside the farming system (chapters 2, 4 and 5) (Figure 6.1). The biophysical levers identified to improve crop and livestock production varied across farm types in terms of magnitude of their impacts. Higher nutrient inputs and nutrient use efficiency would have a greater impact on subsistence farmers whereas, market-oriented and agro-pastoralists would benefit more from investment in equipment and high quality forage production and storage. This underscores the necessity of tailoring options (Descheemaeker et al., 2019) according to farmers' resources and production goals. Ideally, improvement in production at farm level could foster direct exchange of biomass between crop and livestock farms leading to higher nutrient recycling at village level. Based on the role of legumes in alleviating soil fertility mining (chapter 3), I investigated crop diversification with legumes at plot level and its impacts at farm and village level. I first identified diversification options farmers were already familiar with i.e. sorghum-legume intercropping and rotation and sole legume cropping. These options were integrated in a novel serious game developed for the mixed crop-livestock farming system (chapter 4). I furthered my analysis with a multi-level model exploration of crop diversification with legumes (chapter 5). There was a significant trade-off associated with crop diversification between soil fertility improvement and food sufficiency at farm and village level. The same trade-off applied between soil fertility improvement and herd size. As the impacts of crop diversification were more pronounced at farm level, the village level is not an aggregation of impacts at farm level. In fact, when moving from farm to village level, interactions between farms can lead to synergetic or antagonist effects at village level (Grillot et al., 2018a). The reasons being opportunities of interactions (biomass inflows and outflows) within and outside the village. In my case, the possibility for farmers to move out of village to get additional forage as well as grains and crop residues inflows from outside the village to compensate for the lack of forage could explain why village level was less impacted by crop diversification. The choice for a particular legume in crop diversification also mattered, as their impacts on the farming system varied. This brings us back to the dimensions (e.g. soil fertility and crop residues production) of options proposed to farmers which should be in line with their production goals and challenges (Ronner et al., 2021). Additionally, despite agro-ecology being strongly promoted in SSA, higher nutrient inputs and improved nutrient use efficiency in the cropping system will be required for better crop-livestock integration and production. Indeed, the input reduction principle of agro-ecology was shown to be inappropriate in SSA where nutrient input is already limited (Falconnier et al., 2023).

Achieving improved crop-livestock integration will also require income diversification through off-farm activities in addition to biophysical options (chapter 2). Indeed, options identified within the farm still require a certain level of financial investment from farmers which may be difficult given their limited access to financial capital. The potential of off-farm activities in helping farmers escape the poverty trap was confirmed in this thesis (chapter 2). Actually, off-farm revenue is a promising alternative for farmers to get additional income to be reinvested in their farms to increase productivity (Tankari, 2020).

6.3 Multi-level modelling of mixed crop-livestock farming systems

6.3.1 Modelling approach

There are mainly three approaches for building ABMs (Edmonds and Moss, 2004; Le Page and Perrotton, 2018; Sun et al., 2016), including (1) Keep It Descriptive and Simple (KIDS), (2) Keep It Simple and Stupid (KISS), and (3) Keep It a Learning Tool (KILT). The KIDS approach is intended for context-based models with a fine description of socio-ecological processes. The KISS approach is suited for theoretical models with relatively high reproducibility but less contextualization. The KILT approach is between the KIDS and KISS approaches balancing between complexity (model structure) and utility of the model. The ABM developed in this thesis mostly followed the KIDS approach (chapter 5). The objective was to explore the effects of locally-suited options to increase crop-livestock integration and production. Therefore I chose to start with describing all socio-ecological processes I was interested in and then simplify the model as much as possible so that the computation power required for the models runs was minimized. Examples of the socio-ecological processes include direct exchange of biomass between farms and crop yield formation as a function of soil fertility, rainfall and nitrogen inputs, and farmers' interactions. I tried to balance as much as possible complexity (model behavior) and complicatedness (model structure) (Sun et al., 2016) by simplifying agents' behavior using simple rules (from empirical observations) rather than elaborated theories. Nevertheless, the actual land use map of the village was used as basis for spatial interactions. This implied representing the actual number of farms (700) and including a lot of agents (farmers and livestock) moving and interacting across the landscape. Hence, the simplicity of agents' behavior was counterbalanced by the number of interacting agents in the model. As the socio-ecological processes implemented in the model are valid across semi-arid smallholder farming systems, the ABM can be applied to other crop-livestock systems with adjustments (e.g. cultivated crops) to fit local realities.

6.3.2 Model exploration for multi-level analysis of mixed crop-livestock farming systems

The complexity of the studied systems combined with the possibly inherent complicatedness of ABMs can hinder the interpretation model output. Depending on the complexity of the studied system, ABMs may not be formally calibrated and validated as we understand it for statistical or mechanistic models for example. However, it is still possible to explore ABMs to better understand why they produce what they produce. In addition to creating knowledge on ABMs behavior, model exploration helps identifying at within and across levels the most (and the least) relevant socio-ecological processes implemented as well as how much the structure of the model itself influences the model outputs (Borgonovo et al., 2022; Ten Broeke et al., 2016). Indeed, because of the time dimension, the order in which processes are executed in ABMs is important. A simple example is livestock feeding. Are livestock first fed at home and then grazed in the village to get additional forage if they do not meet their requirement? Or is it the other way around? For researchers, model exploration is an important step to build trust in their model (i.e. represent as close as possible the reality), and to explain the extent to which the underlying principles and hypotheses influence the results of their models. Based on a good understanding of model behavior, model exploration continue with exploring the range of model outputs in response to input variables and searching for optimal outputs. It is important to note that model exploration is not a linear process but a continuous one in which the model itself is progressively adjusted if necessary.

6.3.2.1 Sensitivity analysis and challenges for large models

Sensitivity analysis in ABM studies is not that common (Borgonovo et al., 2022), especially in SSA. One reason is probably the computation power and time required to perform even a local sensitivity analysis, to test the effect of each parameters separately on the model output (Ten Broeke et al., 2016). Depending on the model, running thousands of simulations required for a sensitivity analysis is really a challenge. During the development of my thesis, I had the chance to connect to a community of model explorers I was not aware of at the beginning of the development of my model. This community introduced me to the OpenMole (https://openmole.org/) platform they developed (Reuillon et al., 2013). This platform contains several algorithms to explore models for different purpose such as calibration, sensitivity analysis and optimization. In addition, I had access to great computational power through the Montpellier University cluster via CIRAD (Centre de coopération internationale en recherche agronomique pour le développement). Both the computation power of the cluster and the methods available on the OpenMole platform helped in implementing the exploration of my model.

Testing the robustness of the ABM (chapter 5) with a local sensitivity analysis, I revealed the most influential parameters in the model and that parameters influenced each farm type differently. Additionally, the magnitude of these influences did not add up at village level but were lower than at farm level, pointing out the importance of interactions between farms and between the village and the exterior environment (chapter 5). Overall, the sensitivity analysis revealed there was a good balance between lack of sensitivity and oversensitivity of the model. This meant that the model behavior varied according to fluctuations in inputs parameters but these variations were not disproportionate. The model being moderately sensitive to its parameters demonstrated that these parameters were needed in the design of the model. Additionally, the fact that the model response to moderate variations parameters were not disproportionate indicated that the design and the parameters values of the model were good enough to guarantee a robust behavior. Moreover, the sensitivity analysis also help better understand how the hypothesis underlying the model influenced its behavior. For example, I hypothesized that grains and crop residues were always available for purchased no matter the amount concerned. Consequently farms with the highest income could better cope with crop-related parameters variations by purchasing additional grains and crop residues for their households and livestock respectively. However, given the biomass scarcity context of semi-arid Burkina Faso, unlimited grains and crop residues available on market is unlikely to happen. Therefore from the sensitivity analysis I stressed out the importance of analyzing model's results in relation to their hypothesis. Overall, the results of the sensitivity analysis helped better understand the model behavior in relation to its hypothesis and parameters and gave confidence for further explorations.

It is important to point out that I only tested how each parameter affected the model behavior. But given the high number of parameters required to develop an ABM, interactions between parameters when varying them are also important to consider. Further steps in testing the robustness of the ABM will consist of global, rather than local sensitivity analysis (Saltelli et al., 2010). This approach accounts for non-linear effects when varying several parameters at the same time allowing a deeper understanding of model behavior. Nevertheless, the major inconvenience of this approach is that it is even more demanding in terms of computation power and time than the local sensitivity analysis.

6.3.2.2 Beyond sensitivity analysis

Several tools exist beyond sensitivity analysis in model exploration. Depending on the objective, model exploration can also be used to calibrate and optimize models and investigate the range of model outputs. In chapter 5, I went beyond sensitivity analysis and used Pattern Space Exploration (PSE) (Chérel et al., 2015) to identify patterns and trends in model outputs. PSE is a genetic algorithm that looks for the maximum variability of model outputs in response to variations of input parameters. I applied PSE to look for potential trade-offs and synergies associated with land allocation to sorghum and legumes (cowpea and peanut) in the farming system. To the best of my knowledge crop diversification with legumes has never been explored before at plot, farm and village level simultaneously in SSA. The objective was also to discover theoretical farm configurations, leading to increased crop-livestock production compared to the current situations. Perhaps surprisingly, cropping system configurations from the PSE that guaranteed food sufficiency (but not soil fertility) at farm and village levels were close to the current configurations observed in the field. This suggests that farmers are already managing their farms very well in order to remain food sufficient given their limited resources. Additionally, the alternative cropping system configurations that reduced soil fertility mining were drastically different from real-life farms. These configurations could not maintain food sufficiency for most farms and implied smaller herd sizes compared to reality. By using PSE I demonstrated, given the current farm management, a trade-off between soil fertility and food sufficiency on the one hand and soil fertility and herd size on the other hand. Therefore, by considering only crop diversification with legumes as an entry-point, I was not able to propose new cropping system configurations that would reconcile the three objectives of food sufficiency, larger herd size and improved soil fertility.

PSE can be applied to further explore trade-offs and synergies associated with other key levers identified in chapter 2 to improve crop-livestock production. For example PSE can be used to explore other options such as increased fertilization rate and income diversification. Nevertheless, as models are simplification of reality it is important to reflect with farmers on new farm systems emerging from model exploration. Indeed, farmers face many constraints that may not be included in models. An example in our study is the additional labor requirement associated with strip intercropping and how it affects land preparation and sowing in the farm. These aspects were not considered in the model but remain key in adoptability of new farm configurations (Arslan et al., 2022).

6.4 The role of serious game in multi-level exploration of mixed crop-livestock farming systems

6.4.1 Design process of serious games

In socio-ecological systems, serious games offer opportunities for co-learning, governance and inclusive management of natural resources (Janssen et al., 2023). Games have successfully been used for co-learning in farming systems of tropical areas (Sari et al., 2024; Speelman et al., 2014). However, the use of games in research in SSA is still rare (Flood et al., 2018). Actually, playing games is not that common for adults in the study area, so at first I found it risky to involve farmers in game play. I thought they may not take it seriously, or worse, not understand it at all. However, I was positively surprised by farmers' feedback during the test phase of the game. Their knowledge of the farming system was key in selecting the key socio-ecological relations to include in the game. Farmers actively shared their perception of the game, how it fitted their reality and what was missing in the game mechanics. An example is the addition of rainfall variability in the game following one farmer's comments during the test phase. When commenting on the degree of realism of the game, one farmers told me that the game was fine but that everything was always all right in the game. After asking what he meant, I understood that an important challenge faced by farmers every year, which is rainfall variability, was not included in the game. This illustrates the importance of considering farmers' perceptions in the participatory research process.

The development of the serious game in chapter 4 was based on ARDI (Actors Resources Dynamic and Interactions) method (Etienne et al., 2011). I did not organize workshops to directly determine the ARDI but used data from chapters 2 and 3, which already included focus groups and workshops for participatory farming system description. During the development of the game, I organized several informal test sessions to get feedback even from non-specialists of gaming and farming. I combined these tests with ones that were organized with researchers and farmers. I wanted to find a good balance between the complexity included in the game and the ease of playing. Being part of a team of researchers with a systems background, I found it hard to determine which processes to include or not, as all seemed important. However, the research questions and the hypothesis of the study helped to maintain the focus and simplify the game as much as possible without compromising on the processes required to answer my questions and testing my hypothesis.

In addition to the tests organized with farmers, the exploration of the solution space (Sari et al., 2024) of the game also offered an opportunity to explore and improve the game. The solution space represents all the possible outcomes of the game. Ideally solution space exploration should be done during game development to better understand possible game outcomes and the narrative associated. This allows to check whether game outputs fit scientific/farmers' knowledge or not i.e. whether they make sense or not in the local context. Additionally, the solution space exploration can help to assess the extent to which the game outputs are influenced by the hypothesis underlying its development. Moreover, the exploration offered the advantage to be better prepared for game sessions by being aware of all possible outcomes and associated dynamics. In chapter 4, the solution space exploration was done later when the game was already finalized, mainly because of time constraints during the data collection phase of the thesis. Exploring the solution space earlier than game sessions could have allowed to identify particular game outcomes I would like participants to reach individually or collectively. Game sessions' participants could have discussed how to possibly reach these outcomes and even propose alternatives. In fact, depending on the complexity of the game, making a computer version can be time consuming and challenging as it may require advanced programing skills. These reasons could explain why solution space exploration of serious games is still not common. In my case, a computer version of the game helped also beyond solution space exploration. I started developing my game during COVID-19 times. I developed a couple of versions of the physical and computer game simultaneously. This allowed me to test the game with my supervision team (games and system agronomy) located in various locations in Europe and Africa simultaneously (Photo 6.1), and unable to come and visit me in the field due to the COVID-19 travel restrictions. With the computer version of the game, scientists could also play the game, ask questions and give directions on future versions (e.g. simplification required in the game play). This really helped me progressing in my work despite lockdown and offered opportunity to play with anyone with an internet connection in the world. However, updating the physical board game was much easier and less time consuming than its computer counterpart. At some point, with the relaxation of COVID rules in Burkina Faso, I decided to focus on developing the physical game only with test sessions involving farmers and local researchers in order to move faster in my data collection. It was only later when I started analyzing the game session data that I updated the computer game and implemented exploration routines in it.

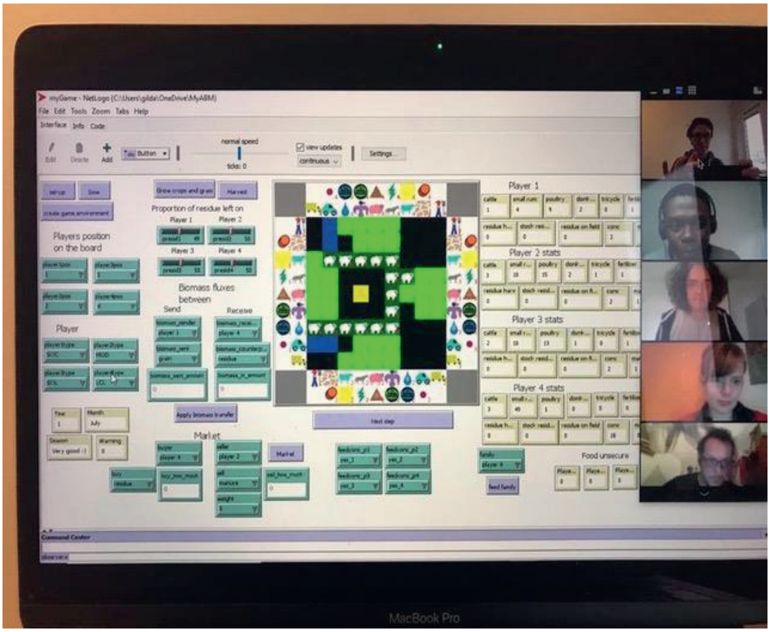


Photo 6.1: online game session with experts (games and system agronomy) during COVID-19 times.

6.4.2 Validity of decision-making during game sessions

A major difficulty in research using serious games is to transpose what participants did in the game into reality (Rodela and Speelman, 2023). In chapter 4, I distinguished between what farmers did in the game and what they would have done differently in real life. The use of a post-game questionnaire (Speelman et al., 2014) right after each game session allowed us to discuss with participants about their understanding of the game as well as the strategy they applied and what they potentially learnt. Participants' answers to the post-game questionnaire were really useful for understanding what happened in each game session and the extent to which farmers' decision-making reflected reality.

Evaluating the impact of game sessions on participants is also a challenge (Rodela and Speelman, 2023). It is possible through direct observations during game sessions and additional debriefing sessions to collect data on what participants learnt during the game (Delima et al., 2021). In chapter 4, I used a post-game questionnaire to know more about what participants learned and the main messages they took away from the sessions. For example, some participants reported they learnt more about cereal-legume intercropping and rotation. These options were introduced in the game to show the advantage of cereal-legume intercropping per unit of land cultivated (Ganeme, 2022) as well as the importance of cereal-legume rotation in maintaining soil fertility (Franke et al., 2018). In addition to the post-game questionnaire and debriefing sessions, Q-method (McKeown and Thomas, 2013; Stephenson, 1935) is another approach to assess opinions. This method can help better understand diverse farm management strategies and the reasons underlying them (Andreotti et al., 2023; Timler et al., 2023). There is potential to better understand impacts of serious games on participants' opinions by applying Q-method before and after game sessions. Overall, combining game sessions with post-game data collection has proven useful in assessing the ability of the game in fostering knowledge sharing with participants (Sari et al., 2024). However, it is challenging to ascertain which changes in participants' behavior are attributable to game sessions or other factors in their environment such as market opportunities.

6.4.3 Complementarity between games and ABMs

Games just like models are simplifications of reality, and games are also models (Villamor et al., 2023). Sometimes, games are a more interactive and simplified version of an ABM (Étienne, 2013). This way they make the knowledge and complexity in models more accessible to a broader audience. Hybrid forms of models and games also exist presenting a game or interactive interface for an ABM and allowing participants to make choices and analyze the impacts of their decisions in real-time (Perrotton, 2015). In this thesis, I moved from simplicity to complexity i.e. I first developed the game and build an ABM from it. This is also the most common approach in combining games and ABMs according to Villamor et al. (2023). The main reasons I took this approach were time constraints in the data collection schedule and the game being easier to develop than the ABM with a KIDS approach. Comparison between game and model outcomes in our case was not appropriate as some model processes such as livestock mobility are not implemented in the current version of the game. Nevertheless the game was useful in better understanding farmers' choices and this understanding was translated in agents' behavior in the model. The ABM helped to further explore options that were not explicit in the model and to integrate the understanding of farming functioning at village level.

6.5 Strengths and weaknesses of the multi-level analysis approach applied in this thesis

In this thesis I performed a multi-level analysis of the farming system ABM (chapters 2, 3, 4 and 5). I used a holistic and participatory approach allowing the contribution of farmers' knowledge, perceptions and recommendations. Using a holistic approach I considered the farming system as a whole, I described the farming system structure and functioning, and I analyzed promising levers to improve crop-livestock integration and production (chapter 2). I furthered explain the current state of the farming system by collecting empirical data on several components of the farming system which turned out to be challenging in terms of organization, labor availability (chapter 3). Hence I could only collect detailed data for one year. However, in response to hazards (e.g. rainfall variability) and other drivers (e.g. policy and market fluctuations) farm management strategies can be adjusted (Huet et al., 2020). Therefore, even if our results are in line with previous studies, they are based on just a snapshot of the farming system. Several years of continuous data collection would allow to better account for the dynamics of the farming system as influenced by its drivers (and notable climate variability, a factor not explicitly considered in this work). Given the context of data scarcity in the investigated farming system, collecting detailed data on each component of the farming system was needed to explore the farming system. Therefore, mainly based on data from chapters 2 and 3, I further explored the farming systems and options to improve crop-livestock integration and production using a serious game and an ABM. The first has the advantage to be more interactive and a knowledge sharing tool whereas the second accounts more quantitatively for complexity of the farming system. Both of them are complementary as data from the game can be used to feed a model and vice versa (Villamor et al., 2023). My participatory approach differed from the companion modelling approach (Étienne, 2013) which starts with a participatory conceptual model that can later be translated into a game used to 'validate' model behavior. Contrastingly, I started by building the serious game together with farmers based on empirical and farmers' knowledge. Building the game first seemed a good solution as it was 'easier' to implement than the model and was easily understood by farmers. Developing the ABM following the KIDS approach took a lot of time and effort and some data required to describe agent behavior originated from game sessions. Due to time constraints, the articulation between the serious game and the ABM was limited to farmers' decision-making and the feedback obtained from farmers during game tests and sessions. The serious game could also have served as a basis for scenario development with farmers that can be quantitatively explored with the ABM. One of the major limitations of our ABM is the lack of flexibility in farmers' decision-making. It could be interesting for the virtual farmers agents in the ABM to continuously adapt their farm management based on experience and influence of other farmer agents in the simulations. One example of decision-making theory is the CONSUMAT framework (Jager and Janssen, 2012), which, in addition to considering the influence of interacting with other humans, also accounts for other aspects driving human behavior such as ambitions, uncertainties, personal needs and satisfaction. There is room to better understand farmers' decision-making process by improving agents' cognition in the ABM (Speelman, 2014) with the possibility to adapt their behavior and comparing agents' choices with those of farmers for various scenarios during game sessions. Improvement of decision-making can be combined with a stylized landscape perhaps still respecting the proportion and distribution of land use in the village. This can significantly reduce the number of farms (e.g. from the current 700 to 100 farms) and thereby decrease the computation power and time required to run the ABM.

6.6 Toward a new framework for co-designing farming systems

The DEED cycle is a participatory framework allowing to communicate complexity with farmers and co-design relevant solutions with them (Descheemaeker et al., 2019; Giller et al., 2011). At the start of my PhD journey, my ambition was to co-design, following the DEED cycle, tailored options to increase crop-livestock production (chapter 1). As I was progressing in the journey and driven by time constraint I had to re-adjust the overall objective of my thesis as completing the co-design phase of the DEED cycle seemed not realistic. In fact, completing the DEED cycle is time-demanding and probably requires more than a 4-year PhD project, especially because of data collection in participatory trials and/or farm monitoring (Huet, 2023). The DEED cycle is not a linear process but involves several potential adjustments in methods or treatments experimented with farmers based on their feedback and data analysis. Additionally, I realized that there is still room to improve the methodological approach to implement the DEED cycle and I had the impression that evaluating the impact of participatory research on communities is missing in the cycle. Therefore, based on my experience in participatory research with farmers I propose the DECODE (Define, Evaluate, Co-design and Decide) approach (Figure 6.2). The DECODE approach is similar to the DEED approach but assumes a stronger stakeholder participation for farming systems co-design. Moreover, the DECODE approach also accounts for research outputs out-scaling, adoption/adaptation of co-designed innovations and addressing related constraints at community level. In fact, the final goal of the participatory approach is to resolve commonly identified issues in a community rather than in a sample of actors involved in the research. Therefore, communicating and extending participatory research results (considering their validity) beyond the scope of research is also important. This will require other actors and financial means that may not be available for researchers. Nevertheless, the process is not meant to be completed by one research project or program but several ones, building on each other's findings and continuously evaluating the impact of participatory research outputs at community level.

The DECODE framework is composed of four phases (Define, Evaluate, Co-design and Decide) and six interrelated steps. The framework is a continuous learning cycle between researchers, farmers and other relevant actors (e.g. seed companies, extension services, NGOs) of the farming system.

- Define. The define phase consists of step 1 of the cycle. Participatory problem definition is made with all actors and research questions are formulated. Several frameworks exist for participatory identification of issues and better understanding of socio-ecological systems in general (Villamor et al., 2023). Examples are the ARDI (Actors Resources Dynamic and Interactions) developed by Etienne et al. (2011) and the DPSIR (Drivers, Pressures, System state, Impacts and Responses) developed by Smeets and Weterings (1999).
- Evaluate. Following the problem and research questions formulations, trials and/or participatory data collection is implemented (step 2). Trials should be preferably installed with farmers in their fields (Falconnier et al., 2017) and the process of farm level monitoring should be explicitly explained to farmers so that they know what to expect (chapter 3). Trials and/or farm monitoring

needs to be periodically evaluated by researchers, farmers and other relevant actors preferably through multicriteria assessment (Falconnier et al., 2017; Lairez et al., 2023). Actually, options tested by researchers, even if they are targeted to a particular component of the farm (e.g. the soil), will most likely also affect other components (e.g. households) of the farm system. Hence the importance of multicriteria assessment considering various dimensions such as productivity, environmental health and profit. Options and related research questions can be adjusted based on results from the multicriteria assessment.

- Co-design. The co-design phase consists of steps 3 and 4. Based on data from step 2 and literature, a serious game is designed together with farmers. The serious game serves as a knowledge sharing platform between actors as well as a virtual laboratory to qualitatively explore the impacts of options tested in step 2 on the farming system. The serious game is/could be complemented with quantitative modelling (e.g. crop/farm models, ABMs). Actually, socio-ecological processes can be oversimplified in games and game outputs are qualitative making it difficult to transpose their results to the actual farming system. Instead, game outputs can be used to build scenarios and narratives that can be confirmed (or not) by results from quantitative and more process-based models. Results from serious games and quantitative modelling must be communicated to all actors in order to decide on the next steps of the research cycle. Because the majority of farmers in SSA are illiterate, communication of research results with illustrated manuals containing pictures already familiar to farmers should be preferred for higher mutual understanding (Dissa, 2023).
- Decide. In this phase, all actors jointly decide in workshops based on the convergence/divergence of opinions to adjust the options tested in step 2 or to scale out the findings to the whole community (steps 5 and 6) (Richardson et al., 2022). This phase offers the opportunity to combine both research and development. One of the potential strength of participatory research is that it leads to readily adoptable options by farmers. Scaling out of these options (innovations) and monitoring the related adoption and constraints can strengthen the ability of participatory research in improving farming systems. This will require training of extension service workers and farmers to make sure the results from participatory research process are properly implemented.

The DECODE framework shared some similarities with the co-innovation framework developed by Rossing et al. (2021). The authors defined three domains, which, in combination, led to co-innovation: (1) the complex adaptive systems perspectives describing socio-ecological relations at various levels, (2) social learning resulting from interactions and knowledge sharing between actors in a system, and (3) monitoring and evaluation of research projects' results. DECODE allows the description and exploration of socio-ecological relations. In addition, through the inclusion of relevant actors in each step of the research

DECODE offers opportunity for knowledge sharing among actors. Moreover, results from participatory research are continuously monitored and eventually adjusted.

In a context of a PhD thesis, I recommend combining either steps 1, 2, 3 and/or 4 with the objective of system description and exploration. If the ultimate goal of the PhD is co-design, then steps 3, 4, 5 and eventually steps 2 should be combined. However, co-design can be done only if at least steps 1 and 2 (corresponding to Describe and Explain phases in DEED) were already completed. In my opinion, it is also possible to combine step 6 with steps 1 and 2 in a PhD thesis with the objective of assessing adoption of innovations and analyzing the related adjustments these innovations might require.

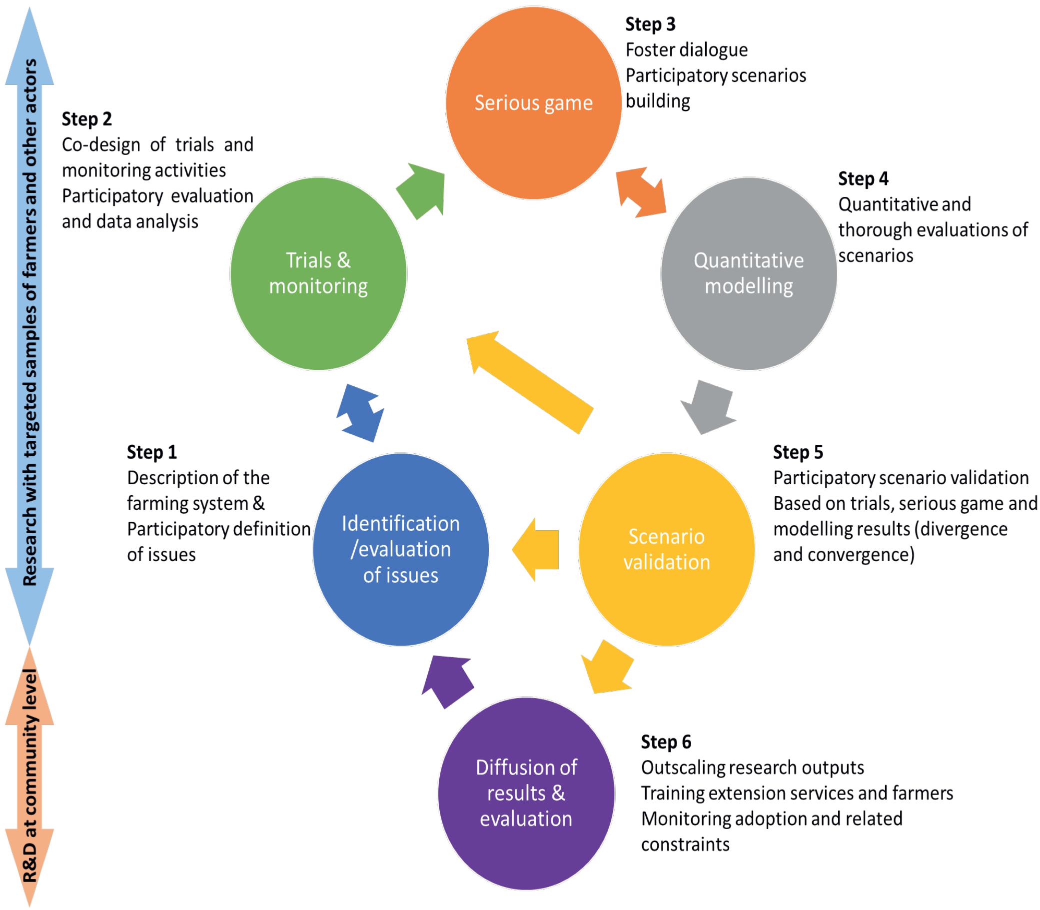


Figure 6.2: DECODE (Define, Evaluate, Co-design and Decide) approach framework to solve commonly identified issues with farmers and relevant actors. R&D = research and development. ARDI = Actors Resources Dynamic and Interactions (Etienne et al., 2011). DPSIR = Drivers, Pressures, System state, Impacts and Responses (Smeets and Weterings, 1999).

6.7 Conclusion

Challenges and opportunities in mixed crop-livestock systems were explored through participatory data collection, modelling and serious gaming with farmers. I analyzed the farming system at three levels: plot, farm and village. The system approach allowed to unravel the complexity in the farming system by considering interactions and feedbacks within and across levels. Additionally, including farmers in the research allowed to better account for locally-relevant social and biophysical dimensions of the farming system. Farmers' participation in serious game sessions confirmed the potential of games in bridging communication gaps between researchers and farmers in SSA. The combination of serious games and quantitative models is a promising approach to foster co-design of sustainable farming systems of SSA. Moreover, I demonstrated that transition toward sustainable farming systems in semi-arid West-Africa starts with intensification of the crop production with higher nutrient inputs and nutrient use efficiency. To intensify their systems, involvement in off-farm activities to get additional income to be re-invested in farming is a promising avenue for farmers. Further studies should explore the impacts of these options on the farming system together with farmers and co-design tailored options to improve crop-livestock integration and production.

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8 Appendix

Appendix 1: Managing biomass in semi-arid Burkina Faso: Strategies and levers for better crop and livestock production in contrasted farm systems

Appendix 2: Can low-input agriculture in semi-arid Burkina Faso feed its soil, livestock and people?

Appendix 3: QUEEN: a serious game to explore mixed crop-livestock systems in semi-arid Burkina Faso

Appendix 4: Crop diversification with legumes improves soil fertility but compromises food sufficiency at farm and village level: results of an agent-based modelling study in semi-arid Burkina Faso

Appendix 1

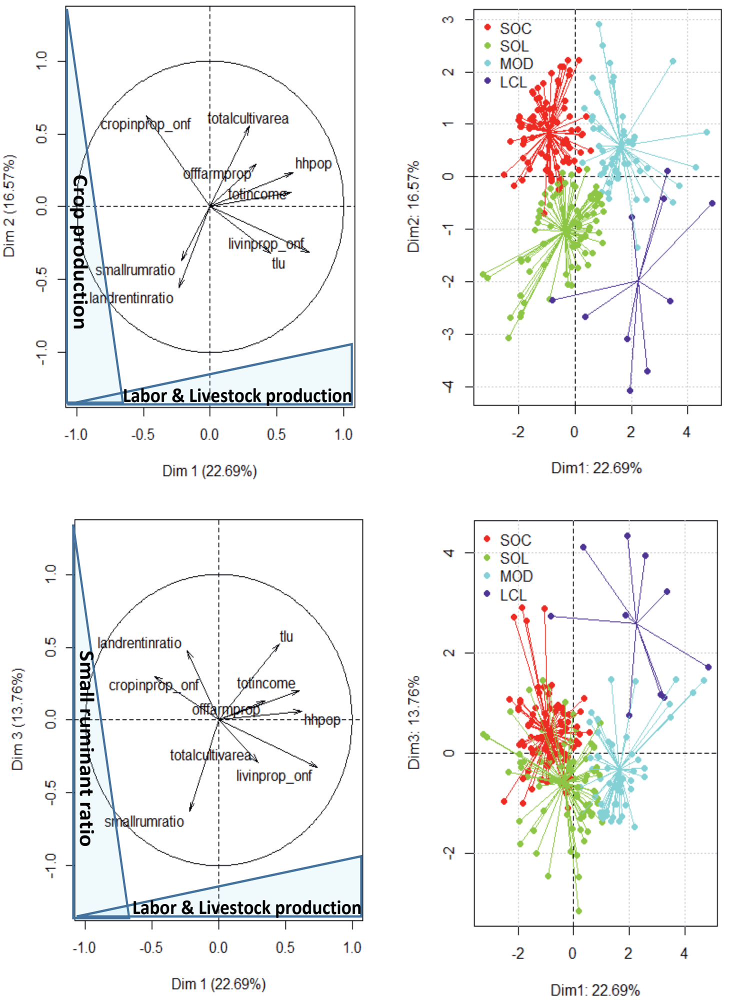


Figure S1: results of principal components analysis and hierarchical clustering performed on pooled survey data from Tansin and Yilou. Four types were identified: SOC (subsistence oriented crop), SOL (subsistence oriented livestock), MOD (market oriented diversified) and LCL (land constrained livestock). Dim 1, 2 and 3 are respectively the first, second and third principal components, the percentages in parenthesis refer to the variability conserved in a given component. hhpop = household size, totalcultivarea = total cultivated area by the household, landrentinratio = proportion of the total cultivated land that is rent by the household, tlu = tropical livestock unit, smallrumratio = proportion of small ruminant in the herd, totincome = annual total income of the household, cropinprop_onf = contribution of crops to the household on-farm income, livinprop_onf = contribution of livestock to the household on-farm income, offfarmprop = contribution of off-farm activities to the household total income.

Table S1: statistics (mean ± standard deviation) of each farm type. Variable values with the same letter are not significantly different between farm types.

	Farm types			
Variables	Subsistence-oriented crop	Subsistence-oriented livestock	Market-oriented diversified	Land-constrained livestock
Household size	7.9±3.7b	6.7±3.1c	12.1±4.3a	15.2±9.1a
Household size per ha	4.3±4.1c	5.1±4.11b	4.3±3.3bc	11.6±7.1a
Total cultivated area (ha)	2.3±1.1b	1.7±0.9c	3.6±1.6a	1.5±0.7c
Share of land dedicated to cash crops	0.3±0.2b	0.3±0.2b	0.4±0.2a	0.2±0.1c
Land rent in ratio	0.1±0.2c	0.2±0.4b	0±0.1c	0.5±0.5a
TLU	2.6±2.4c	3±4.3c	4.6±3.9b	32.5±14a
TLU per ha	1.1±1c	2.4±6.1b	1.7±2.6bc	30±23.7a
Small ruminants ratio	0.3±0.2b	0.5±0.3a	0.3±0.2b	0.1±0.1c
Cattle ratio	0.3±0.3bc	0.2±0.3c	0.4±0.3b	0.9±0.1a
Sorghum yield	971±707ab	1207±912a	1059±705ab	1853±2090a
Cowpea yield	1120±3025a	1371±5003a	1028±4194a	193±407b
On-farm income	58979±98578b	66266±106810b	372006±533076a	522100±388227a
Total income	94035±146077b	82799±126641b	957226±1305914a	612100±497293a
Share of on-farm income from crop production	0.7±0.4a	0.1±0.2c	0.2±0.3b	0.0±0.1c
Share of on-farm income from	0.1±0.2b	0.6±0.5a	0.8±0.3a	0.8±0.4a

Farm types				
Variables	Subsistence-oriented crop	Subsistence-oriented livestock	Market-oriented diversified	Land-constrained livestock
livestock production				
Contribution of off-farm revenue to total income	0.3±0.3b	0.2±0.3b	0.5±0.3a	0.1±0.2b

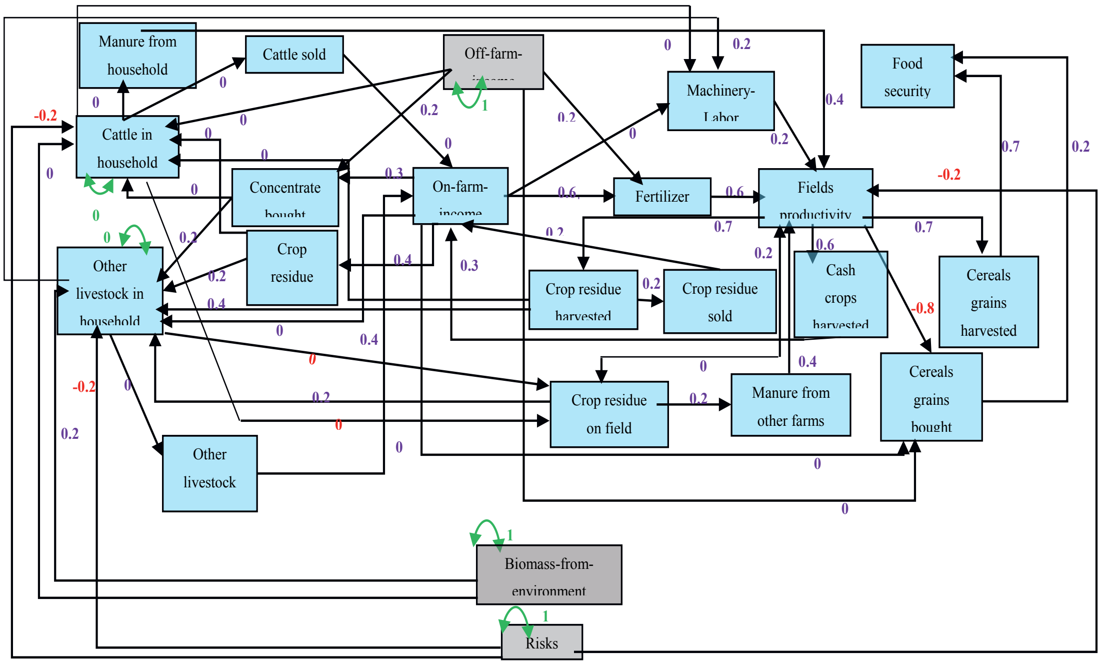


Figure S2 : fuzzy cognitive map of SOC farm type

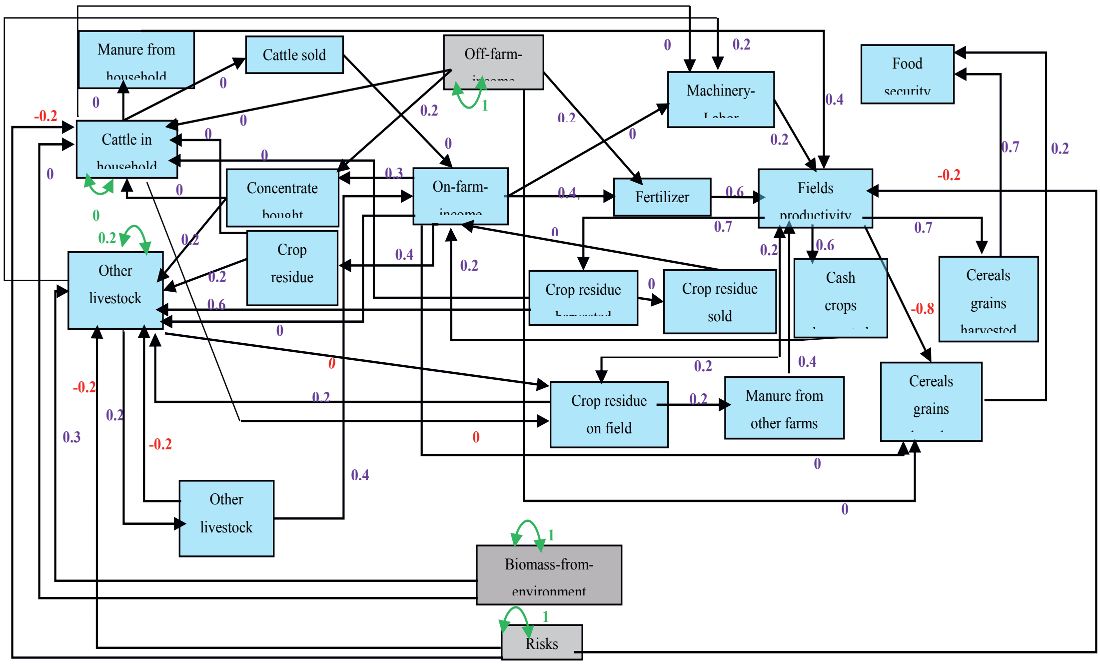


Figure S3 : fuzzy cognitive map of SOL farm type

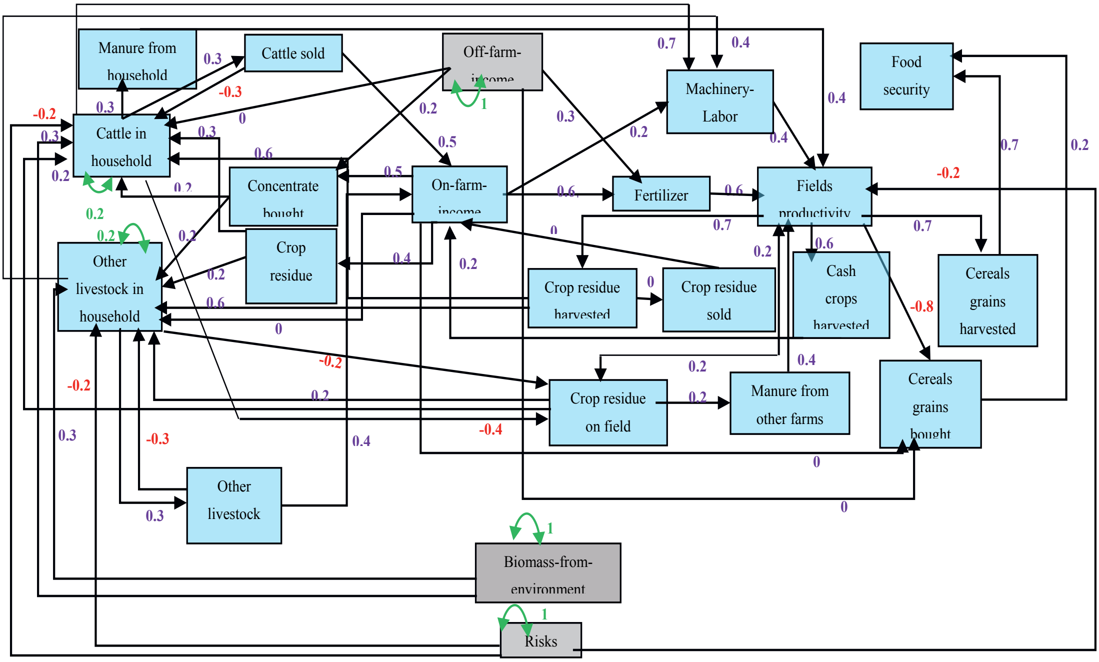


Figure S4 : fuzzy cognitive map of MOD farm type

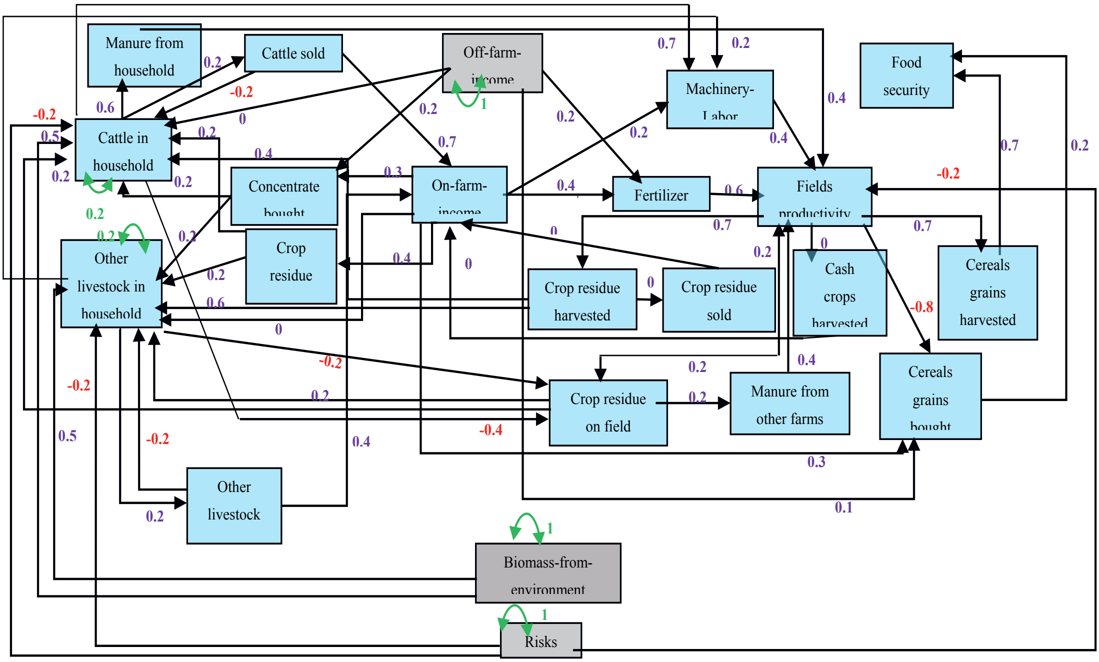


Figure S5: fuzzy cognitive map of LCL farm type

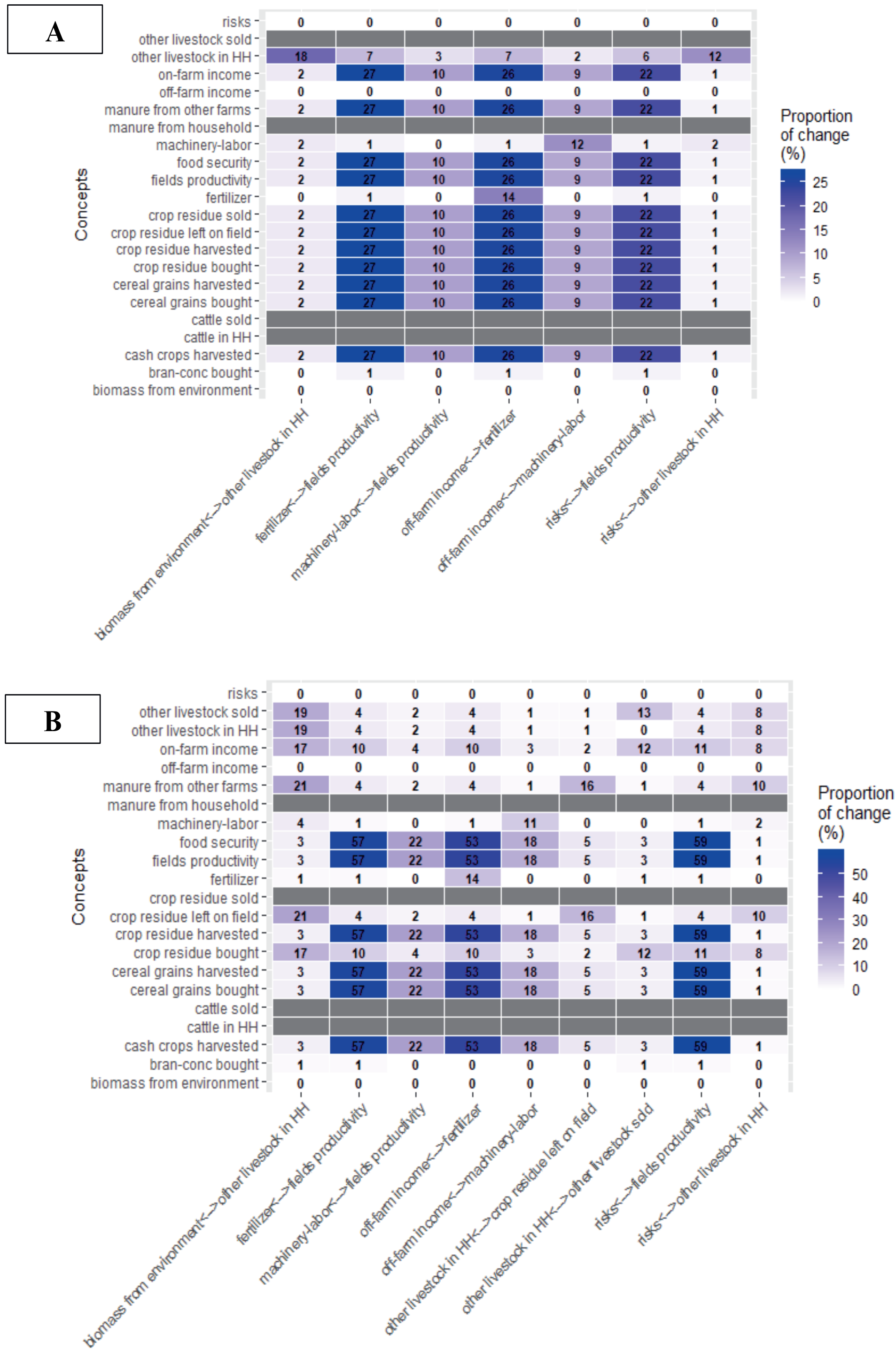
Table S2: general information on fuzzy cognitive maps of each group of farm

	SOC	SOL	MOD	LCL
Number of concepts	22	22	22	22
Number of directed edges	55	55	55	55
Number of positive directed edges	27	28	39	39
Number of negative directed edges	3	4	8	8

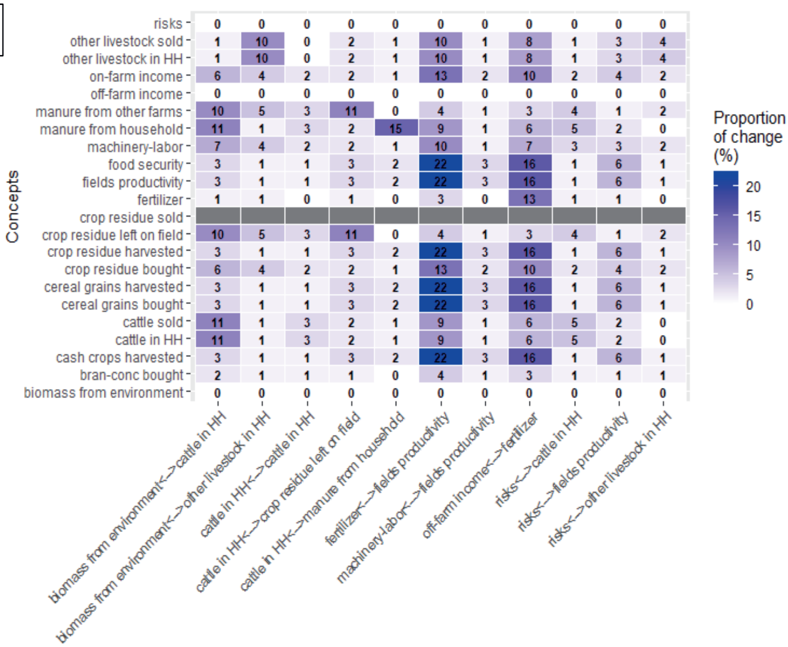
Table S3: changes in weights of directed edges affected by 'residue-contract' and 'market' scenarios

			Directed edge	
Scenario	From	To	Old value	New value
Residue-contract	Crop residue on field	Manure collected from other farms	SOC: 0.2, SOL: 0.2, MOD: 0.2, LCL: 0.2	SOC: 0.27, SOL: 0.27, MOD: 0.2, LCL: 0.2
	Cattle in Household	Manure-compost	SOC: 0, SOL: 0, MOD: 0.3, LCL: 0.6	SOC: 0, SOL: 0, MOD: 0.2, LCL: 0.4
Market	On-farm income	Fertilizer	SOC: 0.6, SOL: 0.4, MOD: 0.6, LCL: 0.4	SOC: 0.78, SOL: 0.52, MOD: 0.78, LCL: 0.52
	On-farm income	Concentrate bought*	SOC: 0.3, SOL: 0.3, MOD: 0.3, LCL: 0.3	SOC: 0.39, SOL: 0.39, MOD: 0.39, LCL: 0.39
	On-farm income	Crop residue bought	SOC: 0.4, SOL: 0.4, MOD: 0.4, LCL: 0.4	SOC: 0.52, SOL: 0.52, MOD: 0.52, LCL: 0.52

			Directed edge	
Scenario	From	To	Old value	New value
	Off-farm income	Fertilizer	SOC: 0.2, SOL: 0.2, MOD: 0.3, LCL: 0.2	SOC: 0.26, SOL: 0.26, MOD: 0.39, LCL: 0.26


A
Concepts
risks
other livestock sold
other livestock in HH
on-farm income
off-farm income
manure from other farms
manure from household
machinery-labor
food security
fields productivity
fertilizer
crop residue sold
crop residue left on field
crop residue harvested
crop residue bought
cereal grains harvested
cereal grains bought
cattle sold
cattle in HH
cash crops harvested
bran-conc bought
biomass from environment
biomass from environment<->other livestock in HH
fertilizer<->fields productivity
machinery-labor<->fields productivity
off-farm income<->fertilizer
off-farm income<->machinery-labor
risks<->fields productivity
risks<->other livestock in HH
Proportion of change (%)
25
20
15
10
5
0
B
Concepts
other livestock in HH<->crop residue left on field
other livestock in HH<->other livestock sold
Proportion of change (%)
50
40
30
20
10
0

C



D

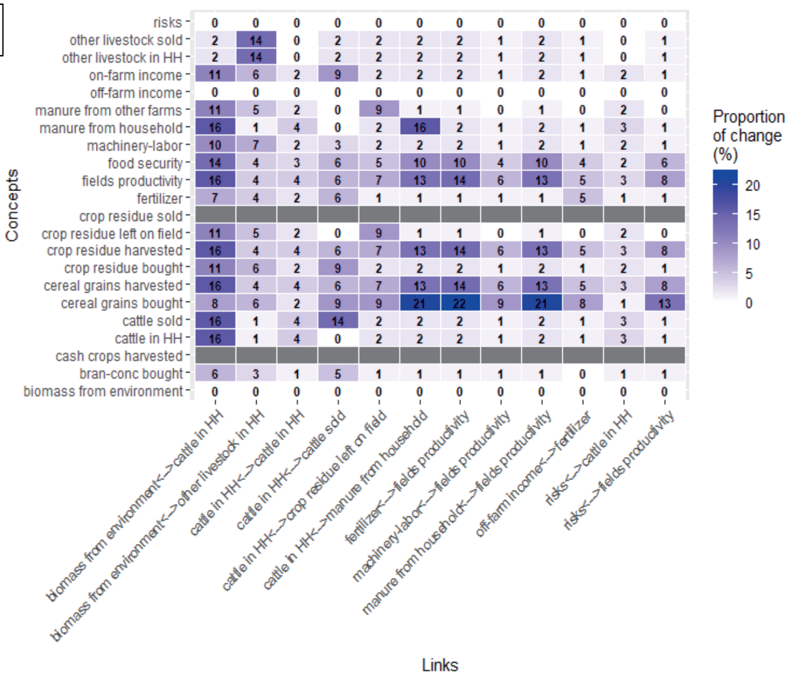


Figure S6 : (A, B, C, D) Results of sensitivity analysis showing mean proportions of change in concepts values for sensitive links (directed edges) for SOC, SOL, MOD and LCL respectively. The gray cells correspond to infinite (or close to) values as result of dividing the standard deviation by a mean being zero or a number close to zero. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock.

Appendix 2

Figure S1: form used by famers to collect data on the amount and type of feed provided to livestock each day

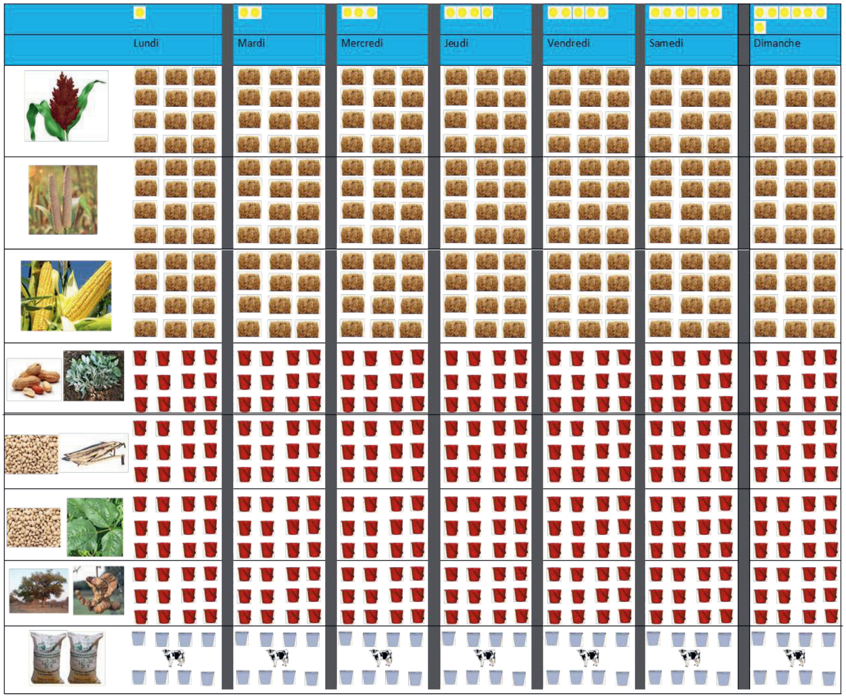


Table S1: Feed characteristics. GE = Gross Energy. ME = Metabolizable Energy. MP = Metabolizable Protein. DM = Dry Matter

	Sorghum straw	Millet straw	Maize straw	Peanut straw	Cowpea pods	Cowpea haulm	Piliostigma pods	Concentrate feed
GE (MJ/kg DM)	18.1	17.7	18.2	17.8	18.2	17.9	n/a	19.25
ME (MJ/kg DM)	7.3	6.3	6.9	7.9	7.2	9	6.9	11.2
Crude protein (% DM)	3.7	5.2	3.9	11.1	12.7	13.7	10.4	29.6
MP (g/day)	18.6	28.6	19.9	50.3	53.1	54.8	60.1	75.5
ME/GE	0.40	0.36	0.38	0.44	0.40	0.50	0.44*	0.58

**Average value of all feeds*

Table S2: Livestock daily metabolizable energy and protein requirements for maintenance. MJ = Mega Joules. 1 cattle = 0.7 TLU. 1 sheep = 0.1 TLU. 1 goat = 0.1 TLU. 1 donkey = 0.5 TLU. 1 TLU = 250 kg. TLU = Tropical Livestock Unit.

	cattle	goat	sheep	donkey
Protein requirement maintenance g	110.66	25.71	25.71	85.98
Maintenance energy requirement MJ	34.80	7.30	6.10	26.93

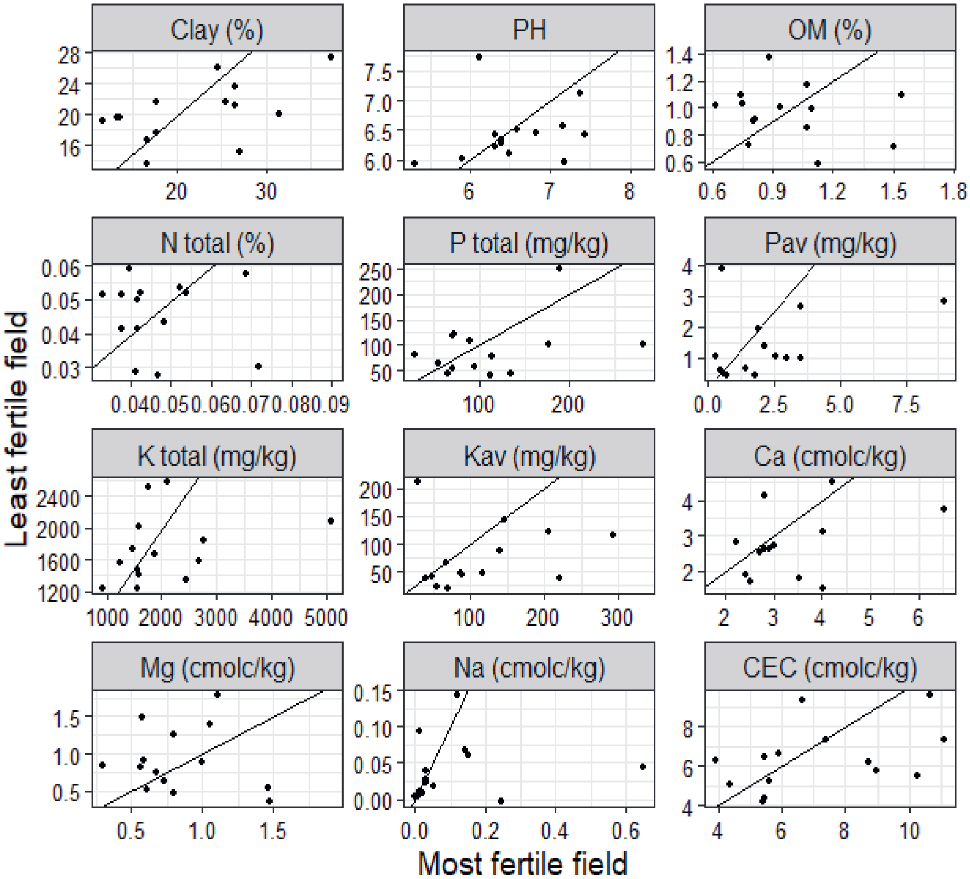
Table S3: linear correlation between field level nitrogen balance and the area cultivated. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

Farm types	Correlation coefficient	P-value
LCL	-0.32	0.2
MOD	-0.04	0.8
SOC	0.06	0.7
SOL	-0.06	0.7
All	-0.07	0.37

Table S4: linear correlation between field level nitrogen balance and the house-field distance. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

Farm types	Correlation coefficient	P-value
LCL	0.17	0.51
MOD	0.005	0.97
SOC	-0.15	0.35
SOL	0.12	0.46
All	0.1	0.22

Figure S2: soil analysis results in the most and least fertile fields designated by farmers. N, P, K are respectively nitrogen, phosphorus and potassium. Pav and Kav stand for available phosphorus and potassium resp. OM = organic matter, Ca = calcium, Mg = magnesium, Na = sodium. The black lines are the 1:1 lines.



Appendix 3

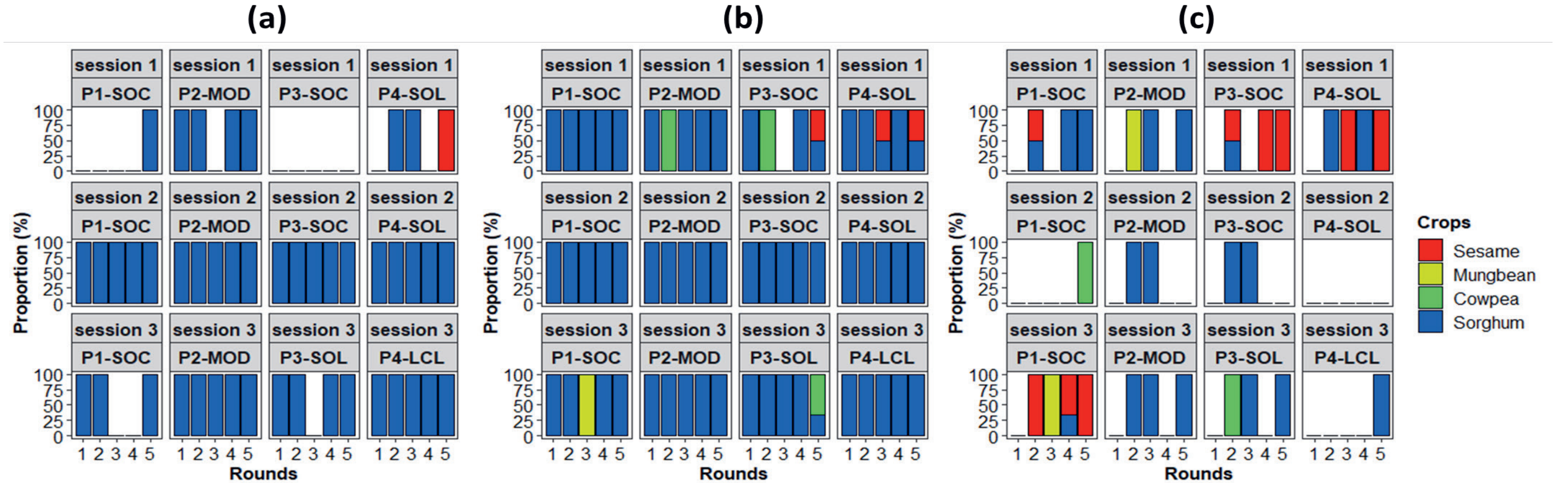


Figure S1: fertilizer (a), manure (b) and mulch (c) allocation to crops. Blank proportions imply no fertilizer/manure/mulch was applied in a given round.

Table S1: sum of inputs applied to fields, items sold and purchased during game sessions.

Sessions	Inputs applied		
	Manure	Fertilizer	Mulch
Session 1	35	21	20
P1-SOC	9	3	3
P2-MOD	5	8	6
P3-SOC	8	3	4

Sessions	Inputs applied		
	Manure	Fertilizer	Mulch
P4-SOL	13	7	7
Session 2	46	21	7
P1-SOC	10	6	1
P2-MOD	15	5	4
P3-SOC	10	4	2
P4-SOL	11	6	0
Session 3	41	28	18
P1-SOC	8	5	9
P2-MOD	8	7	4
P3-SOL	9	7	4
P4-LCL	16	9	1

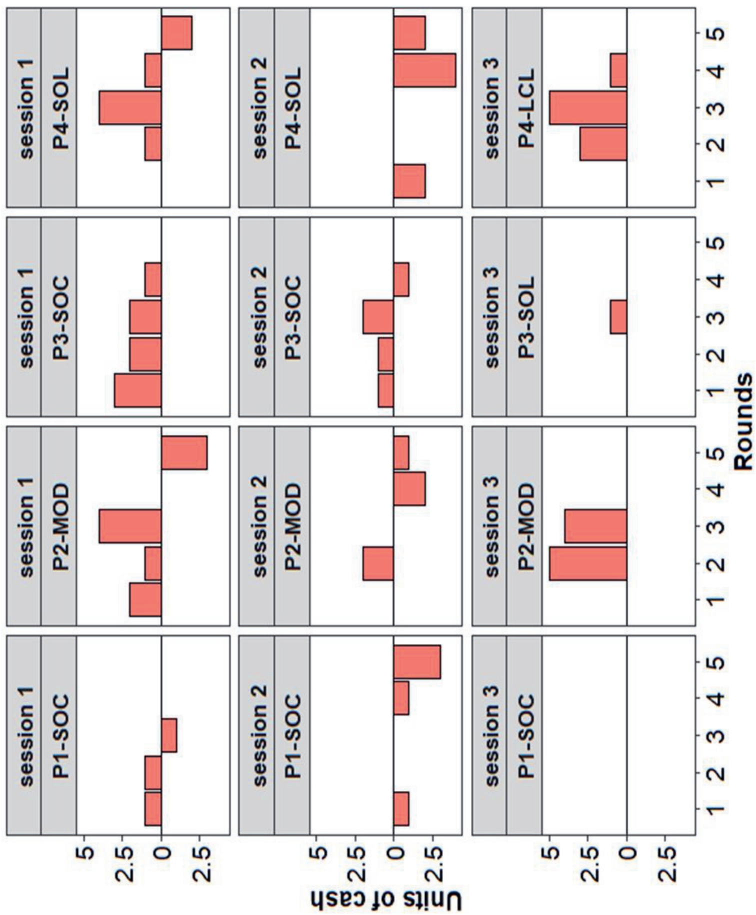


Figure S2: average grains bought and sold during game sessions. SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL).

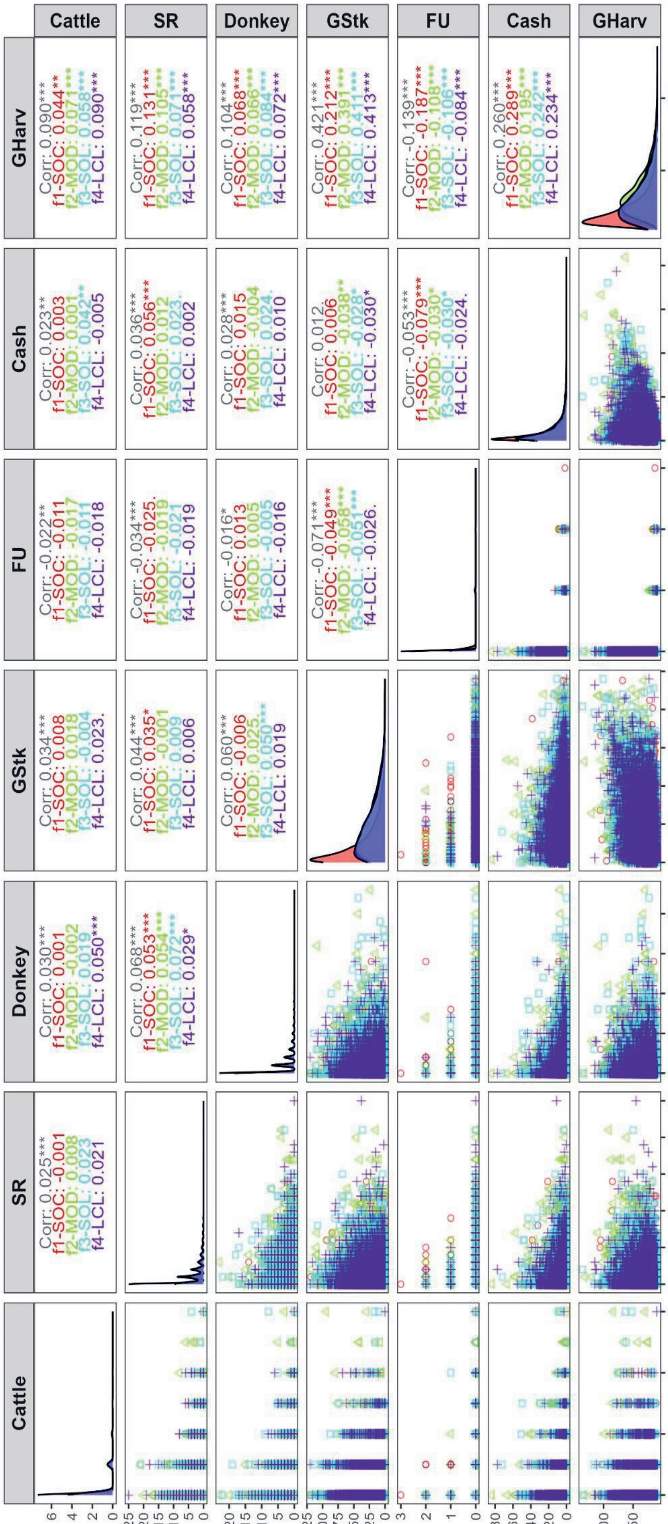


Figure S3: correlations between key outputs of the game. Values were plotted for the last round and last step of the game, except for grains which represented the amount of grains harvested. f1, f2, f3 and f4 refer respectively to participant 1, 2, 3 and 4. SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL).

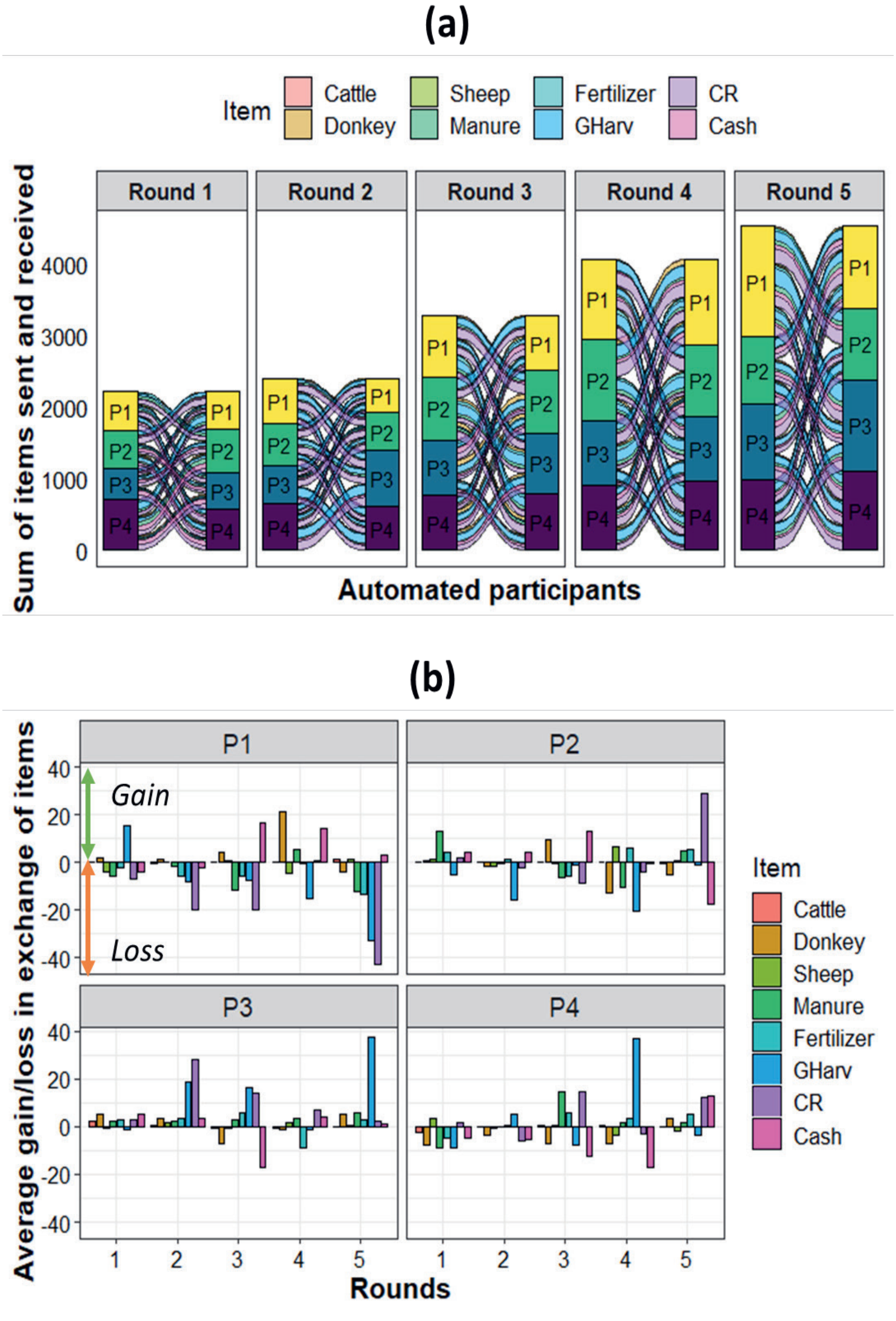


Figure S4: Exchange of game items between participants in all game rounds in simulations (a). Average gain/loss of participants in exchanges (b).

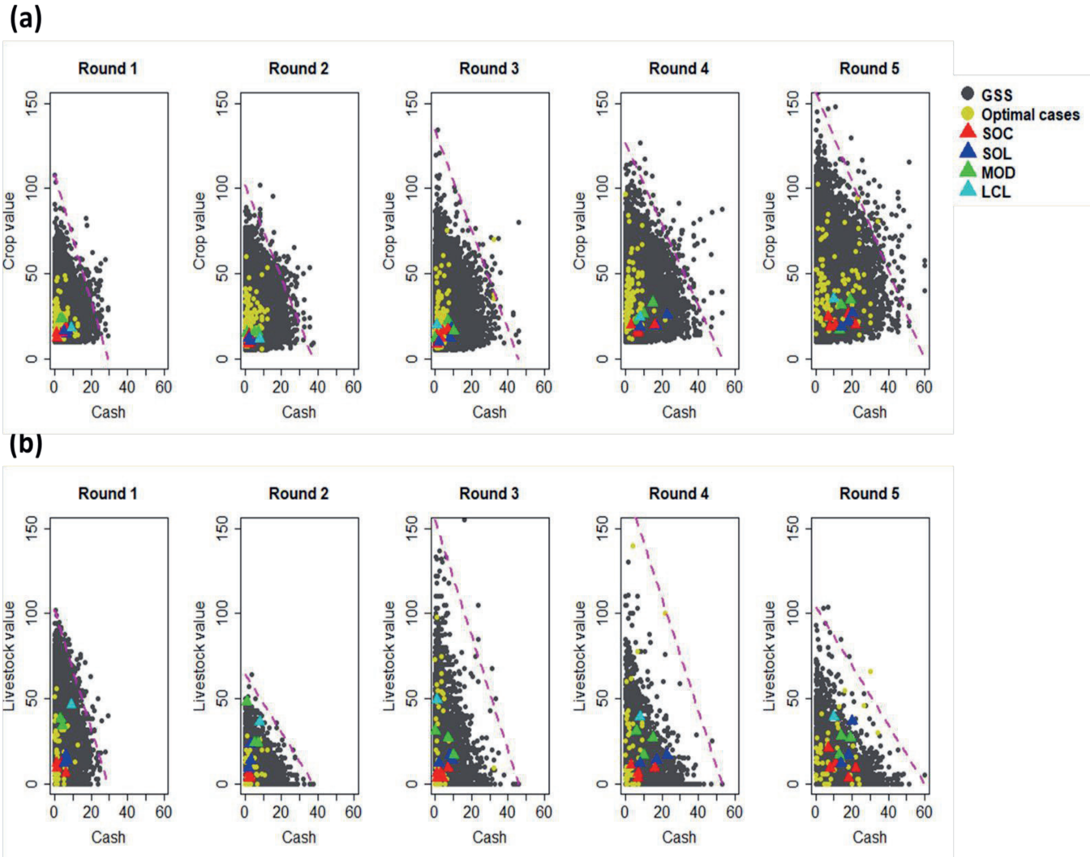


Figure S5: projection of each participant outcomes at the end of the each round of the game in the solution space. GSS = Game solution space exploration results for each automated participant. Optimal cases = automated participants in the best simulations of GSS regarding crop, livestock production and cash. SR = small ruminants. Participants farm type: SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock; MOD = market-oriented and diversified and LCL = land constrained and livestock (LCL). The dashed line in magenta symbolically represents the maximum of each plotted variables that can be obtained in combination.

Pre-game questionnaire

What is your relation with player 1?

	Friend		Brother/Sister		Husband/Wife
	Neighbor		Acquaintance		Religious leader
	Political leader		Traditional chieftaincy		Other:

What is your relation with player 2?

	Friend		Brother/Sister		Husband/Wife
	Neighbor		Acquaintance		Religious leader
	Political leader		Traditional chieftaincy		Other:

What is your relation with player 3?

	Friend		Brother/Sister		Husband/Wife
	Neighbor		Acquaintance		Religious leader
	Political leader		Traditional chieftaincy		Other:

What is your relation with player 4?

	Friend		Brother/Sister		Husband/Wife
	Neighbor		Acquaintance		Religious leader
	Political leader		Traditional chieftaincy		Other:

Post-game questionnaire

1- What did you want to achieve in the game?

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2- How did you achieve it?

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3- Did you manage to achieve your goal? (Y / N)

3-1- If no, why?

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3-2- If yes, which part/resource of your farm help you achieve your goal?

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3-3- If no, what prevent you from being more successful?

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4- What do you think about crop residues being available to all farms, no fence or protection possibility?

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4-1- Concerning crop residue produced management, what would have you done differently in real life?

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……

4-2- You exchanged/did not exchange biomass (grain, residue, livestock, manure) with other players, why? (Only if applicable)

……

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……………………………………………………………………………………

4-3- Do you exchange your biomass (grain, residue, livestock, manure) in real life (Y/N) Why?

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……

4-4- You gave away some biomass (grain, residue, livestock, manure) to other player(s) (Only if applicable)

4-4-1- Why?

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……

4-4-2- How are the persons who benefit from your biomass gifts in real life related to you?

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………

5- Your interactions (discussions, suggestions, exchange of biomass) with other players in the game were driven by:

Check all that apply

	Friendship		Family relation		Leadership
	Better prices as compared to market		Necessity (hungry livestock or family member)		Success of other players in the game
	Other:				

6- Which player(s) suggestions influence your decisions in the game? Why?

Fill by order of importance, e.g.: 1st, 2nd, 3rd

	Player 1		Player 2
	Player 3		Player 4

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7- How did you feel playing this game?

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8- Was there anything surprising or new that you notice/learn playing?

………

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Appendix 4

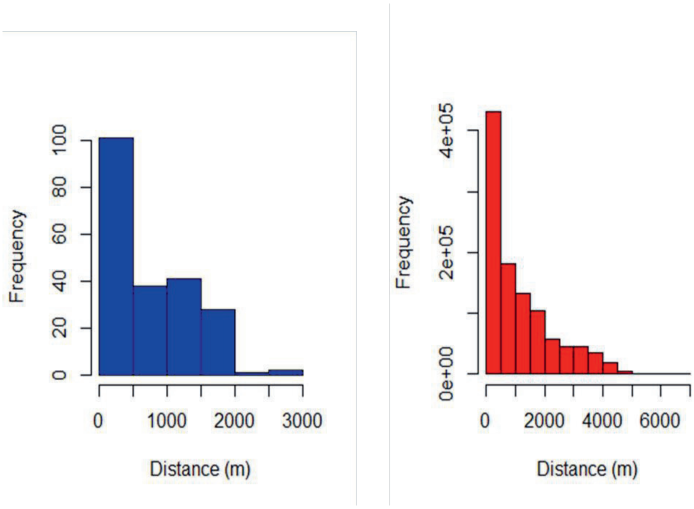

Figure S1: distributions of distance between farmers' settlements and their fields. Blue and red histogram are respectively from field observations and model.

Table S1: parameter settings for crop modelling.

Category	Variables	Details
Plot	Field size	1 ha
	Slope	0
	Slope direction	0
	Savannah/forest/cultivated fields/degraded soil	cultivated fields
Soil type		
	Soil type	Sandy loam
	Soil depth	120 cm
	Ground hardness/surface condition	good conditions
Initial conditions	Preceding crop	the crop to simulate
	Biomass produced by preceding crops	Aerial biomass: 3 t/ha sorghum. 0.8 t/ha legumes. Root biomass: 0.9t/ha sorghum; 0.2 t/ha legumes. ratio root:shoot = 0.3
	Crop residues on soil	0 kg/ha
Crops	Species	*Sorghum bicolor, Vigna ungiculata, Arachis hypogea*
	Cultivar	Sorghum: CSM63E. Cowpea: TVU3644. Peanut:Chinese
Soil tillage	Soil preparation	Animal traction

Category	Variables	Details
	Date	June (14)
	Tillage depth	10 cm
Sowing	Date	June (20)
	Method	Pocket (hills)
	Planting density	Sorghum, cowpea and peanut: 9 plants/m²
	Inter and intra-row spacing	Sorghum: 80cm between rows, 40 cm intra-row ---- Cowpea 80cm between rows, 40 cm intra-row ----- Peanut 80cm between rows, 40 cm intra-row
	Depth	4 cm
Fertilization	Fertilization plans	See Fertilization plans sheet
	Form	Fertilizer (NPK) and/or manure.
	Fertilizer/Manure composition	NPK(23%N-10%P-5%K 2%Mg+3%S+0,3%Zn)----Manure (1.3%N, 0.5%P, 1.4%K, 29.1%C, C:N ratio = 22.38)
	Application dates	14 June = 100% Manure ----- NPK = 50% 2 weeks after sowing and 50% 4 weeks after sowing
	Method	Broadcast (fertilizer), buried at 10 cm (manure)
	Inoculated legumes	No
Cleaning	Method	Manual (hoe)
	Dates	2 and 4 weeks after sowing
Irrigation	Irrigation	No
Pesticide and herbicide	Herbicide/Pesticide application?	No
Harvest	Harvested product	Grains and crop residues
	Harvest stage	Grains maturity

Table S2: fertilization plans used in crop modelling

	Manure dry weight (kg/ha)	Manure (kg N/ha)	Fertilizer (NPK) (kg N/ha)
FP1_O1	0	0	0
FP1_O2	769.2	10	10
FP1_O3	1538.5	20	20
FP1_O4	2307.7	30	30
FP1_O5	3076.9	40	40

Plan 2

	Manure dry weight (kg/ha)	Manure (kg N/ha)	Fertilizer (NPK) (kg N/ha)
	Manure dry weight (kg/ha)	Manure (kg N/ha)	Fertilizer (NPK) (kg N/ha)
FP2_O1	769.2	10	0
FP2_O2	1538.5	20	0
FP2_O3	2307.7	30	0
FP2_O4	3076.9	40	0
	Plan 3		
	Manure dry weight (kg/ha)	Manure (kg N/ha)	Fertilizer (NPK) (kg N/ha)
FP3_O1	0	0	10
FP3_O2	0	0	20
FP3_O3	0	0	30
FP3_O4	0	0	40
	Plan 4		
	Manure dry weight (kg/ha)	Manure (kg N/ha)	Fertilizer (NPK) (kg N/ha)
FP4_O1	384.6	5	5
FP4_O2	1153.8	15	15

Table S3: prices per kg of sorghum, cowpea and peanut used in the model. Prices (FCFA) are average from direct observations. 1 FCFA = 0.0016 USD.

Sorghum	Cowpea	Peanut
500	1200	500

Summary

Mixed crop-livestock systems have potential for higher nutrient recycling and limited nutrient import than specialized crop or livestock systems. However, crop and livestock production in mixed farming system of sub-Saharan Africa (SSA) remains far from optimal and faces several challenges such as fast growing population and land degradation. Numerous studies attempted to find solutions to unravel these challenges and improve crop-livestock production by focusing on particular components of the farm system. However, farm systems are made up of components interacting between each other, implying for example that a 'good' solution at plot scale for soil fertility improvement may not be in line with households' income increase at farm scale. Research that considers this complexity at different scale levels and combines social and biophysical dimensions of the farming system is scarce in SSA. This thesis aims at determining how to improve crop-livestock integration and production in mixed farm systems with a particular focus on semi-arid Burkina Faso. A holistic approach was used considering the farming system as a whole with interactions within and across scales (plot, farm and village). The investigation was done in collaboration with farmers to account for farmers' preferences and constraints.

In chapter 2, a household survey and focus group discussions were organized to collect data on farm structure, functioning and interactions. Diversity of farms was determined using a statistical typology (hierarchical clustering) backed up by a rule-based typology. There were two subsistence farm types differing by the intensity of crop (SOC) and livestock (SOL) production. A market-oriented and diversified (MOD) farm type cultivated the largest area on average, with larger herd size than subsistence farms. On average half of their revenue came from off-farm activities. Finally, the land constrained and livestock (LCL) farm type cultivated the smallest area and owned the largest herd size. Biomass production and management varied across farm types. Highest sorghum yield (the main staple food) was recorded for LCL whereas SOC had the lowest yields. Crop residues were firstly intended for livestock feeding. There was a positive relation between herd size and the proportion of crop residues harvested. Exchange of biomass occurred between farms but was rare. We further explored key levers to improve biomass production and management using Fuzzy Cognitive Maps (FCMs). The FCM analysis revealed that subsistence farms would benefit more from income diversification and improved nutrient use efficiency through the combination of adequate mineral and organic fertilizers. Higher forage production (through use of dual-purpose cereals or legumes) combined with improved storage conditions (e.g. ensilage) can reduce LCL and MOD farms dependence on forage from grazing land. Additionally, scenario analysis with FCM revealed that there is little room for improvement of crop-livestock production based on exchange of crop residues and manure between subsistence and other farm types. On the opposite, policies targeting subsidies on

inputs (e.g. fertilizers and concentrate feed) combined with off-farm opportunities had higher potential in improving crop-livestock integration and production.

The investigation continued with a detailed a one year farm monitoring to collect data on all components of the farm systems (177 fields, chapter 3). Twenty-two volunteer farmers, representing the diversity of farms identified in chapter 2, were involved in the data collection especially in recording the daily amount and type of feed provided to livestock. In addition to livestock feed, herd size and mobility in and out of the village was recorded every two weeks. The influence of livestock grazing on crop residues left on the soil in the fields was also evaluated through weekly measurements in the most and the least fertile field of sorghum of each monitored farm. Crops grown and their arrangements, nutrient inputs and outputs in all fields of each volunteer farm were recorded during the cropping season. Inflow and outflow of biomass (grains, fodder, concentrate feed, manure and livestock) in each farm were recorded weekly. The amount of biomass directly exchanged between households was measured on a weekly basis. Based on the detailed farm monitoring data, nitrogen balance and nitrogen use efficiency were calculated. The average negative nitrogen balance (-12 kg N/ha/year) and nutrient use efficiency of 175% implied soil fertility mining in the cropping system for all farm types. There were mainly three sources of nitrogen in the cropping system. The first was legume through nitrogen fixation from atmosphere, the second was manure and the third was fertilizer. Legumes alleviated soil fertility mining by adding 15 kg N/ha/year in the cropping system. However, the small proportion of legumes in intercropping and sole cropping did not allow to completely offset soil fertility mining. There were almost no crop residues left in the fields at harvest in the least fertile fields of sorghum. However, in the most fertile fields, on average an amount of 736 kg/ha of crop residues was left. Nevertheless, this amount quickly decreased (26-75 kg/ha/week) and after ten weeks all the crop residues were grazed by livestock. As reported by farmers in chapter 2, crop residues were mainly harvested to feed livestock. Farmers particularly valued legume residues which they did not leave in the fields but harvested entirely. The gap between livestock metabolizable energy required and directly provided by farmers was calculated throughout the monitoring period. A considerable gap (73% on average) was found for all farm types, and it was largest for LCL farms (93%). The latter relied more on feed from the grazing land and mobility out of the village to feed their large herd size. Other farm types, except SOL, also moved a small part of their herd out to the surrounding villages in search for feed. All farm types depended on external concentrate feed (cotton seed cake and sorghum bran) which provided on average 22% of the metabolizable energy provided to livestock. Similarly, Piliostigma (*Piliostigma reticulatum* DC. Hochst) pods contributed on average to 13% of the total feed provided by farmers. Three quarters of the monitored farms were food self-sufficient. Two thirds of the non-self-sufficient farms had people to land ratios higher than three. Exchange of biomass varied across farm types. Mainly, LCL farms received crop residues from SOC and SOL farms and in exchange of manure. SOC farms received more grains as aid from other farms.

However, because of the limited amount of biomass exchanged, there was no significant effect on crop production and households' self-sufficiency.

Chapter 4 consisted of a participatory exploration of the farming system with a serious game named QUEEN (QualitativE Evaluator of farm productioN) to better understand farmers decision making in their farm management. The development of the game was an iterative process involving farmers and researchers. A digital version of the game was developed as an agent-based model, which allowed to explore the solution space of the game as the range of possible outcomes. In a total of 30000 runs, automated participants (APs) took random decisions at each step of the game (i.e. no long term strategy/objective). Three game sessions were organized with real-life participants (RPs). A post-game questionnaire was used to collect data on RPs' perceptions of the realism of the game, what they learnt, what they were trying to achieve and what they actually did. Moreover, game outcomes of RPs and optimal outcomes from the solution space were compared. Strategies of RPs during game sessions and APs leading to optimal outcomes were also compared. The game was played with four participants representing the four farm types identified in chapter 2. Resources (e.g. cattle and number of plots) of each participant at the start of a game session reflected the farm type each participant belonged to. Results of the game sessions indicated that RPs were trying to achieve different goals than just increase as much as possible crop and livestock production as well as cash income. These goals included for example maintaining their resources or increasing their herd size, which resembled our observations in the field. RPs and optimal game outcomes were similar in terms of livestock value and cash. However, crop values of optimal outcomes were higher than RPs'. While optimal simulations led to higher crop production than RP sessions, they also implied strong dependence on market to get crop residues to be used as mulch and a change in herd structure. These apparent advantages of the optimal simulations were due to the game rules and underlying assumptions (e.g. permanent resources availability in market) and are not realistic in a context of biomass scarcity. Moreover, cattle being perceived as a prestigious animal, it is also unlikely that farmers would replace them with donkeys. Because RPs did not think about cracking the game, they remained as much as possible close to their reality and the solution space exploration showed that their farm management led to outcomes that were close to the best achievable in the game.

Finally a multiple scale modelling of mixed crop-livestock systems considering socio-ecological relations was applied in chapter 5. An agent-based model (ABM) was developed based on data from chapters 2, 3 and 4 as well as literature. The ABM explored the farming system at plot, farm and village scale simultaneously. The robustness of the ABM was tested with a sensitivity analysis. The ABM was further explored with a Pattern Space Exploration (PSE). PSE is a genetic algorithm which helps determine the possible range of outputs of a model given variations in its input variables. PSE was used on the ABM to explore potential synergies and/or trade-offs associated with crop diversification with legumes within and across scales. Based on the role of legumes in alleviating soil fertility mining in the cropping system, the impact of crop diversification on the farming system at plot, farm and village scale was explored. Crop diversification options with legumes included varying land allocation in sole and intercropping. The intercropping options included strip intercropping of sorghum with cowpea and peanut as well as the traditional intra-hill sorghum-cowpea intercropping. The impact of sorghum-legumes rotation was also explored. The results of the ABM simulations for the current situation revealed food sufficiency at village scale but not always at farm scale despite exchange of grains between sufficient and non-sufficient farms. Crop yields, livestock mobility and manure collection were strongly determined by rainfall. The negative nitrogen (N) balance observed at farm scale in chapter 3 was confirmed at farm and village scale with the ABM. Both crop fields and grazing land were concerned. No spatial distribution of N balance and nitrogen use efficiency (NUE) was observed at village scale, probably because nutrient application was not a function of distance between fields and farm settlement, and because access to market (seed, grain, crop residue) was equal in all the landscape. The sensitivity analysis demonstrated that the most strongly influencing factors varied per farm type and from farm to village scale. Crop-related parameters such as rainfall and organic nitrogen mainly influenced subsistence farms (SOC and SOL). They were also affected by variations in livestock reproduction rate in the model. LCL farms, with the largest herd size, were mainly influenced by livestock-related parameters such as daily livestock feed intake, livestock starvation and reproduction thresholds, daily manure excreted and the amount lost through volatilization and leaching. Interestingly, MOD farms having by far the highest total income were hardly affected by any parameter. Their level of income allowed them to better cope with variations in the systems. At village scale, the most influential parameters were both crop and livestock-related. PSE results showed trade-offs associated with crop diversification with legumes given the current level of nutrient inputs. Diversification improved soil fertility but at the expense of food sufficiency and herd size at farm and village scale. The trade-offs were more pronounced for subsistence farms (SOC and SOL). Additionally, the results from PSE demonstrated that current farm management targeted food sufficiency in the short term at the expense of soil fertility mining. Increased nutrient inputs and nutrient use efficiency would be required to foster crop-livestock integration and production.

In conclusion, this thesis provided evidence of the relevance and usefulness of combining social and ecological relations in the farming system through participatory research and modelling. Promising levers were found to improve crop-livestock integration and production but they differed according to the diversity of farms. Given data scarcity in mixed crop-livestock systems of sub-Saharan Africa, the detailed data provided on all components of farm systems will surely be useful for future studies. The serious game developed in this thesis can be adapted to other mixed farming systems. It is a powerful tool to bridge communication gaps between farmers and researchers, explore and co-design relevant and tailored options to improve mixed farming system productivity. The simplicity and the qualitative aspects of the game should be combined with quantitative modelling to further confirm (or not) the results from the game sessions with farmers. Based on the overall approach applied in this thesis, a new framework for exploration, co-design and dissemination of participatory research was proposed.

Acknowledgments

The PhD journey has been a challenging and exciting marathon allowing me to continuously improve as a scientist and person. I would not have completed the journey without the support of my research team and of many colleagues, friends and family members. First of all, I thank God for giving me the working environment with the right people at the right time so that I could achieve my objectives and deliver expected results. I thank the biomass team (my supervisors) who trusted me from the beginning of my thesis and continuously provided guidance throughout my journey. I could not have dreamt for a better supervision team for my PhD. My main supervisor and promotor Katrien Descheemaeker has always been a source of inspiration for me, especially her ability to combine hardworking with efficiency. Thanks Katrien for the scientific, financial and psychological support during my PhD especially in difficult times such as the lockdown due to covid-19 and inflation due to war in Ukraine. When it comes to the concrete and applied dimensions of my work, Myriam Adam has always been the most attentive of my supervisors. I really learnt a lot from your critical thinking about anything I was trying to do, especially in the moment I focused more on number crunching than the added value of my work. David Berre, is probably the supervisor I feel the closest to, probably because of his age, his personality and his creativity when discussing science. Thanks David for teaching me that science can also be fun. You always encouraged me in approaching research with innovative point of view. The funniest and the most enjoyable part of my thesis was the development and application of the serious game. The development of the serious game would not have been possible without the supervision and support of Erika Speelman. Her expertise in gaming and participatory modelling allowed me to quickly learn from a field I knew nothing about before the start of my PhD. I also thank Etienne Delay, who showed me how to go beyond model development and build trust in models. You were the first person to give me confidence in my ability to build a game and a model from scratch in a period of my PhD journey I doubted I could reach my objectives. I was lucky to learn so many skills about agronomy, data analysis, serious game and companion modelling from experts in my team.

I did my fieldwork in Burkina Faso, where I met a lot of remarkable persons who assisted me in many ways. The CIRAD staff in Ouagadougou always offered guidance and facilitate data collection. I particularly thank Aissata Diallo Diallo, Mathieu Karambiri (Big Mat), Aminata Ganeme (the RR), Rasmane Bagagnan (Big Ras), Juliette Lairez, Louis-Marie Rabouin, Jean-Marie Douzet, Julie Dusserre and Serge Marlet.

In my journey I greatly benefited from the farmers network of the AMSP association. A particular thank to Roger Kabore, the head of AMSP. Thanks for providing the logistics and personal necessary to implement my data collection.

My data collection would not have been possible without the commitment of three great colleagues and friends: Nock Ouedraogo aka le Berto, Souleymane Sawadogo and Touwende Sawadogo. Measuring and tracking biomass was a though work especially in the period around harvest. However, you never spared your efforts to give the best data quality possible. A particular attention to Adama Dione, the first master student I supervised. Your commitment to always provide excellent results led to significant progress in my thesis, especially concerning its spatial dimension.

This research would not have been possible without the collaboration of local authorities and farmers in Yilou and Tansin. I particularly thank the 22 volunteer farmers who actively contributed to farm monitoring data collection and participatory modelling. I learnt a lot from your knowledge and perception of the farming system.

Living in Ouagadougou and Kaya was a great experience because of friends I made there. I particularly think about the families of Mohamed Drame, Soumaila Kabore, Song Naba and Olivier Sanou. You really made me feel home.

My first family when I arrived in the Netherlands in 2019 was the African Choir of Wageningen, a vibrant group of amazing people. I enjoy the rehearsal, the good music and talk with you all. Special thanks to Joshua, Severin, Christella and Bernard (Prof). I am also grateful for Pauline Eichenseer and Tenzin Wangchuk who made my life easier and funnier in Wageningen during the first months.

I was also lucky to meet some old friend from Benin: Romaric Kouiho, Gauthier Bohissou, Serge Alindekon, Martial Houessou and Buenas Agbohozo. Thank you all for the moments of joy and happiness we usually share in great occasions. I want to particularly thank Romaric and his wife Pamela for the priceless support they gave me especially during the last stretch of my PhD, thank you guys.

I send a special thought to the whole SESAM team with its great professors and students. Our collaboration went beyond academia and I am really happy to collaborate with such creative and inspiring people.

I also thank all my colleagues in PPS for advice concerning science in general and life in the Netherlands. Special thanks to Linda and Karen, two amazing ladies who always provided assistance especially when It comes to heavy and sometimes boring administrative processes. I am also glad I had two PPS colleagues from Benin with whom I share the ups and the downs of the PhD, thanks Deo-Gratias Hougni and Marius Assogba. I particularly thank my colleagues from the coolest office of Nova: Durk Tamsma, the happiest man of PPS and my paranymph, Neo Mathinya always fun and nice, Rika Sari and Danny Saputra the greatest parents, Cameron Ludemann the certified athlete. Collaborating with you all brought a lot of joy and airiness in my days.

And because a tree is nothing without its roots, I am very grateful to my family for all the support, encouragement and kindness. I thank my mother and my father Edith Azonsi and Rodolphe Assogba. Words would not be enough to testify my gratitude for the care, love and support you never fail to provide me. God bless you more. Cedric and Larissa Assogba, my brother and sister, I am glad we are always together as a team, supporting each other in growing and achieving the best possible in our lives. Special thanks to Eloise and Hortense Azonsi and Norbert Allale, you truly are a source of inspiration for me.

A special thanks to Toto Irene Obossou, Ayanfe'm, my Queen. Your love, support and affection throughout my PhD journey were key for my success. Thanks for always being there for me, pushing me to give my best on all occasions and giving me comfort when times were challenging. You truly are a formidable person.

PE&RC Training and Education Statement

With the training and education activities listed below the PhD candidate has complied with the requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises of a minimum total of 32 ECTS (= 22 weeks of activities)

The C.T. De Wit Graduate School PE&RC PRODUCTION ECOLOGY & RESOURCE CONSERVATION

Review/project proposal (4.5 ECTS)

Modelling biophysical and socio-economic interactions in agro-sylvo-pastoral systems of sub-Saharan Africa

Post-graduate courses (6 ECTS)

Research method support training workshop; McKnight foundation (2019)

Multi-platform international summer school on agent-based modelling & simulation for renewable resources management; CIRAD (2019)

La modélisation d'accompagnement: mettre des acteurs en situation pour partager des représentations et simuler des dynamiques; LISODE (2020)

Invited review of journal manuscripts (1 ECTS)

Agricultural Systems: interplay: a game for the participatory design of locally adapted cereal legume intercrops (2022)

Competence, skills and career-oriented activities (3.94)

Competence assessment; WUR (2019)

The essentials of scientific writing & presenting; WUR (2022)

Scientific writing; WUR (2022)

Writing the general introduction and discussion; WUR (2022)

Scientific integrity/ethics in science activities (0.3 ECTS)

Ethics in plant and environmental sciences; WGS (2019)

PE&RC Annual meetings, seminars and PE&RC weekend/retreat (1.5 ECTS)

PE&RC First year's retreat (2019)

PE&RC Last year's retreat (2023)

Discussion groups/local seminars or scientific meetings (6 ECTS)

SESAM Discussion group (2020-2022)

Sustainable intensification of agricultural systems discussion group (2022-2023)

International symposia, workshops and conferences (10.4 ECTS)

DP ASAP; Bobo-Dioulasso, Burkina Faso (2019)

McKnight foundation community of practice; Ouagadougou, Burkina Faso (2020)

Conférence intensification durable; Dakar, Senegal (2021)

Tropentaag conference; Prague, Czech Republic (2022)

Global sorghum conference; Montpellier, France (2023)

BSc/MSc thesis supervision (6 ECTS)

Évaluation spatio-temporelle de la biomasse aérienne à Yilou dans la zone semi-aride du Burkina Faso entre 2014 et 2020

Analyse de la gestion de la biomasse en zone semi-aride du Burkina Faso

About the author

Gildas G. C. Assogba was born in 1993 in Cotonou, the economic capital of Benin. He obtained his high school degree in 2010 and pursued agricultural studies in University of Abomey-calavi, Benin. He obtained in 2013 his bachelor degree in agronomy and his last year internship was about water management associated with a small dam in Glazoue in the central region of Benin. He later worked one year as a consultant and a research assistant on one of his university project aiming at optimizing irrigation and fertilization of pineapple in the plateau of Allada, south of Benin. In 2017, he obtained his master degree in agronomy with a specialization in rural engineering and water control. His master thesis focused on the evaluation of the variability rainfall and rainy seasons' length across Benin using both observed and satellite data. He continued his studies in Cheikh Anta Diop University of Dakar, where he obtained in 2018 another master degree in agroforestry, ecology and adaptation. For the related master thesis, he developed and validated a statistical model to quantify pearl millet and cowpea roots biomass in intercropping in order to better understand complementarity and/or completion associated with various millet-cowpea intercropping systems. In November 2018, he was selected for a PhD position at Wageningen University and officially started in January 2019. His PhD was a collaboration between Wageningen University and the French Agricultural Research Centre for International Development (CIRAD). Since August 2023, he started a 3 year postdoc position with Wageningen University. His work involves participatory field trials, and multilevel modelling of farming systems in the southern region of Malawi.

Funding

The research described in this thesis was financially supported by the 3F project funded by McKnight Foundation, the WUR-SESAM program funded by the WUR-INREF, and the IPCC scholarship program funded by the CUOMO Foundation.

Financial support from Wageningen University for printing this thesis is gratefully acknowledged.

Cover design by Gildas G. C. Assogba

Printed by Proefschriftmaken on FSC-certified paper


set-up
set-up-village
one_year_sim
x_years_sim
n_year_sim 20
On Off export-outputs?
Farm types proportions (%)
n_soc 36
n_mod 26
n_sol 32
n_kl 6
Households in the village
vsize 100
current year
1
day of year
1
Crops : proportion of plots
soc_sorghum 72
sol_sorghum 70
mod_sorghum 69
kl_sorghum 82
soc_cowpea 13
sol_cowpea 15
mod_cowpea 17
kl_cowpea 14
soc_peanut 15
sol_peanut 15
mod_peanut 14
kl_peanut 4
soc_sesame 0
sol_sesame 0
mod_sesame 0
kl_sesame 0
soc_mungbean 0
sol_mungbean 0
mod_mungbean 0
kl_mungbean 0
soc_mucuna 0
sol_mucuna 0
mod_mucuna 0
kl_mucuna 0