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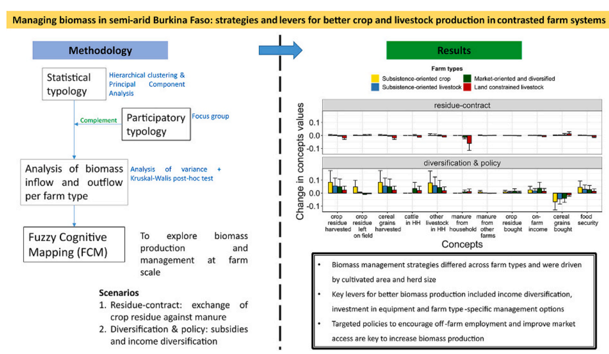
HIGHLIGHTS

- Complementing a statistical typology with a participatory typology increases the legitimacy of a farm diversity assessment.
- Biomass management strategies differ across farm types and were mainly driven by cultivated area and herd size.
- Fuzzy Cognitive Mapping was useful for representing and exploring farm-scale biomass management strategies.
- Key levers for better biomass production include income diversification, investment in equipment and farm type-specific management options.
- Targeted policies to encourage off-farm employment and improve market access are key to increase biomass production.

GRAPHICAL ABSTRACT



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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

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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).

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. 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.

2.1. 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. 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.

2.3. 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.

2.4. Farm typology and related biomass management

Two different farm typologies were established. First, a statistical

Table 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.

typology was based on variables reflecting resource endowment and production goals (Table 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 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.

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.

2.5. 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 (3.1 and 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 (Fig. 1, purple box). For each of these concepts, the production, inflow and outflow were considered (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 (Fig. 1, green box), and production factor concepts, such as fertilizer, field productivity and machinery-labor (Fig. 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 Fig. 1 but in Fig. 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.

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

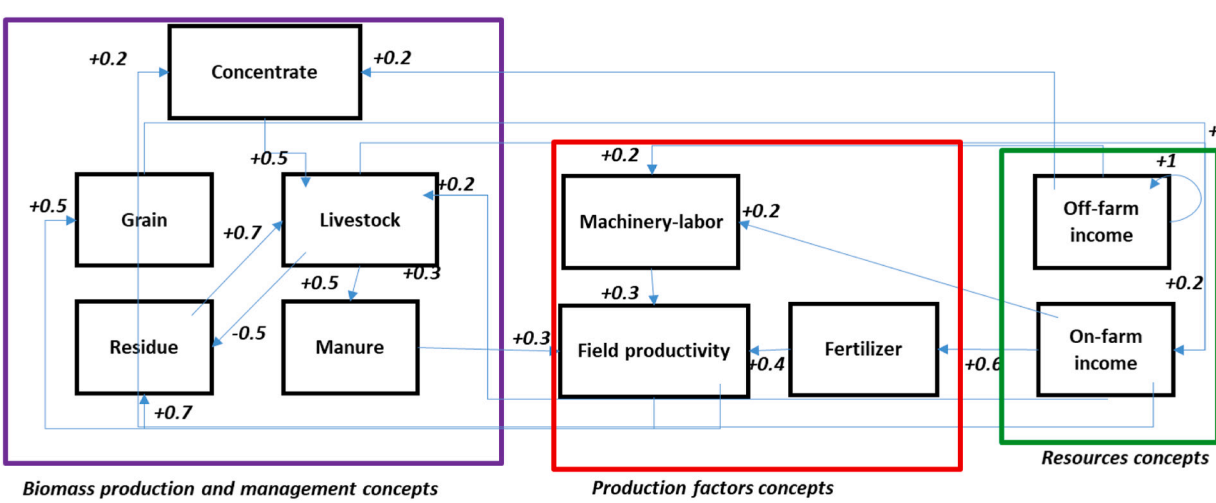


Fig. 1. Representation of a simplified FCM (Fuzzy Cognitive Map) that forms the basis for the farm type-specific FCMs. Black squares are the concepts, the arrows represent the directed edges (links), and values on the directed edges are the weights associated to the relation between two concepts. In 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.

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.

2.5.2. 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).

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.

3. Results

3.1. Farm diversity

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.

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 (Fig. 2). Farmers divided each type (except the subsistence type) into three subgroups according to resource endowment (Fig. 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.

The participatory typology agreed well with the statistical typology for the subsistence-oriented farms (Fig. 3). Indeed, 90% of the farms classified as subsistence-oriented by farmers were also classified statistically as subsistence-oriented (SOC or SOL) farms (Fig. 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 (Fig. 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.

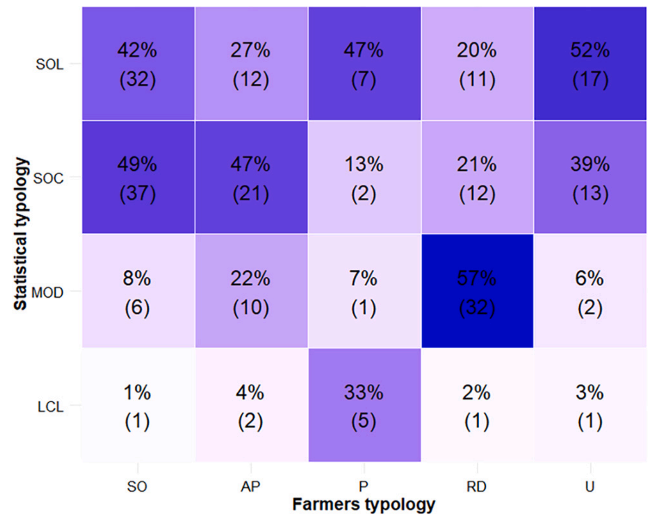


Fig. 3. Comparison between statistical and farmers' typology. The percentages represent the proportion of a farm (farmers' typology) corresponding to a certain statistical farm type. In parenthesis are the number of farms. SO = subsistence oriented; AP = Agro-pastoralist; P = Pastoralist; RD = Revenue-diversified; U = Unclassified. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock.

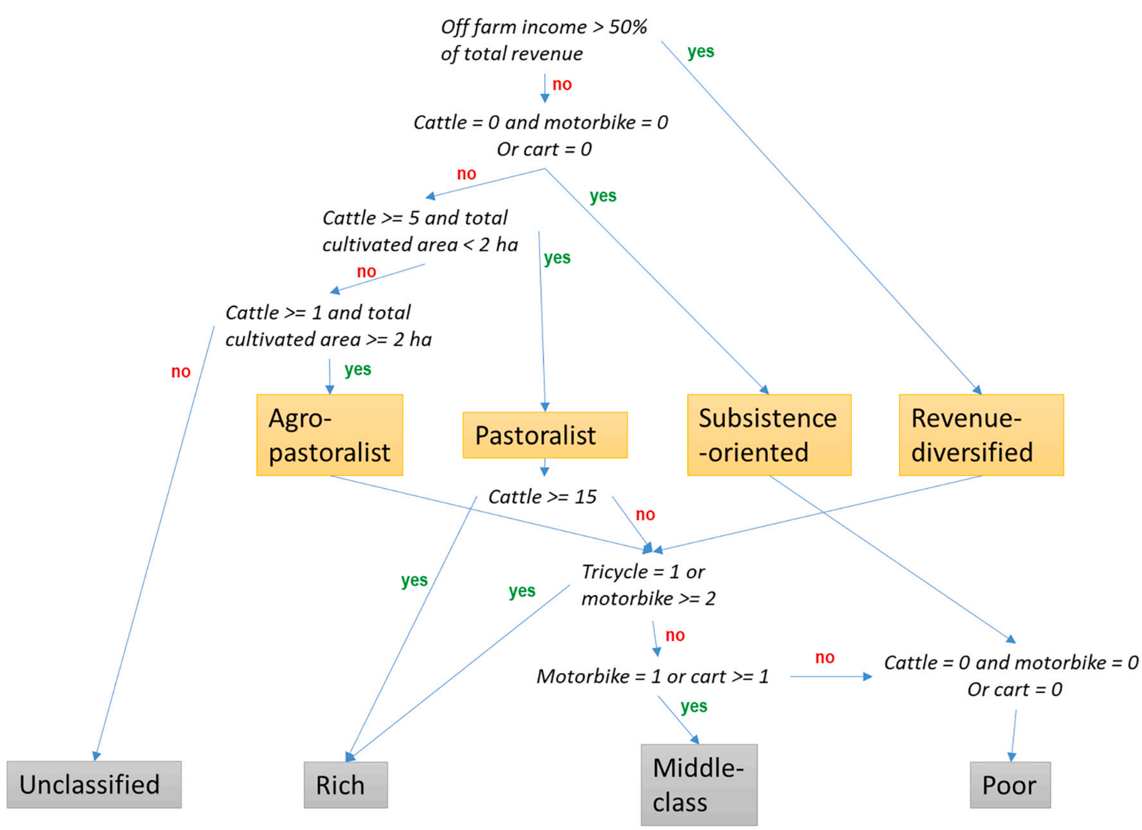


Fig. 2. Rule-based typology, established using information from focus group discussions with farmers.

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 (Fig. 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, Fig. 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.

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 (Fig. 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.

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). 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). In terms of biomass outflow, only SOC and SOL farms sold their residue, with SOC farms selling the most (Table 2 & Fig. 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.

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.

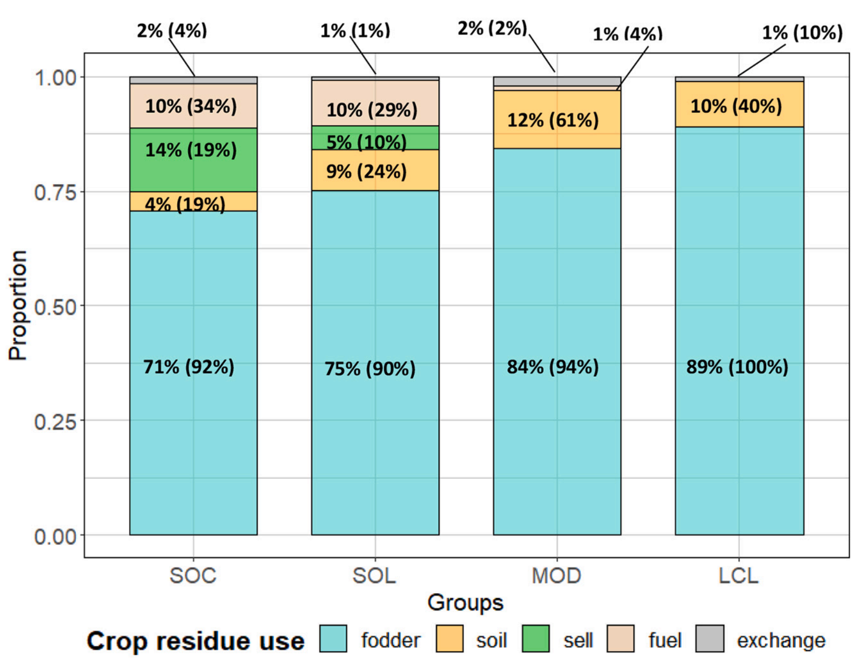


Fig. 4. Proportion of total sorghum residue biomass that is used for different purposes. In parenthesis, the proportion of farms using their crop residue for a certain purpose. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock.

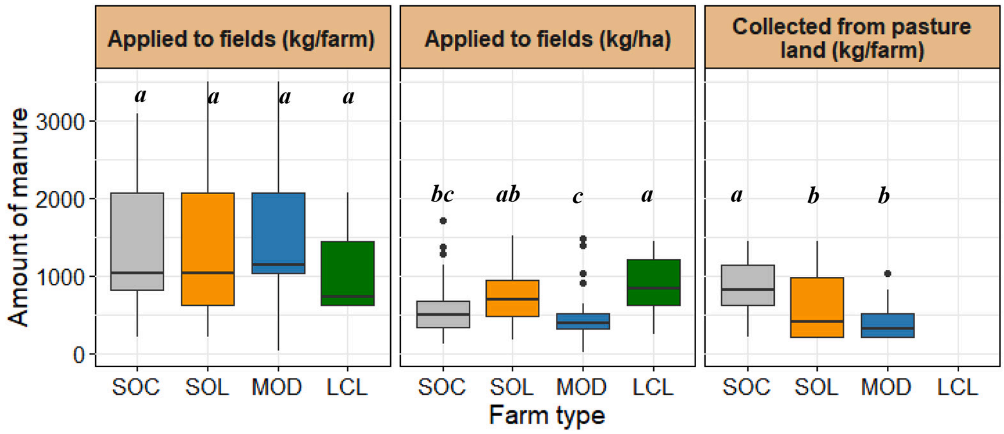


Fig. 5. Amount of manure (dry matter) applied to fields and collected from pasture land by all farm types. Boxplots with the same letter are not significantly different at $p = 0.05$. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock.

3.3. Farm level modelling using fuzzy cognitive mapping

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 (Fig. 6).

After calibration, we obtained values of the concepts at equilibrium that reflected the pattern of biomass management for the four farm types (Fig. 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 (Fig. 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.

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 (Fig. S6) 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 (Fig. 8A). A similar remark applied to SOL type for the link between biomass from environment and - livestock (except cattle) (Fig. 8B). The fertilizer – field productivity link is the only biophysical link affecting all farm types' crop production, concentrate feed (except LCL) and grain inflow (Fig. 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 (Fig. 8D and Fig. 8F). The off-farm income – fertilizer link also caused important variation in the FCM outputs especially for SOL and SOC types (Fig. 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 (Fig. 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.

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 (Fig. 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 (Fig. 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 (Fig. 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.

4. Discussion

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

Table 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	%

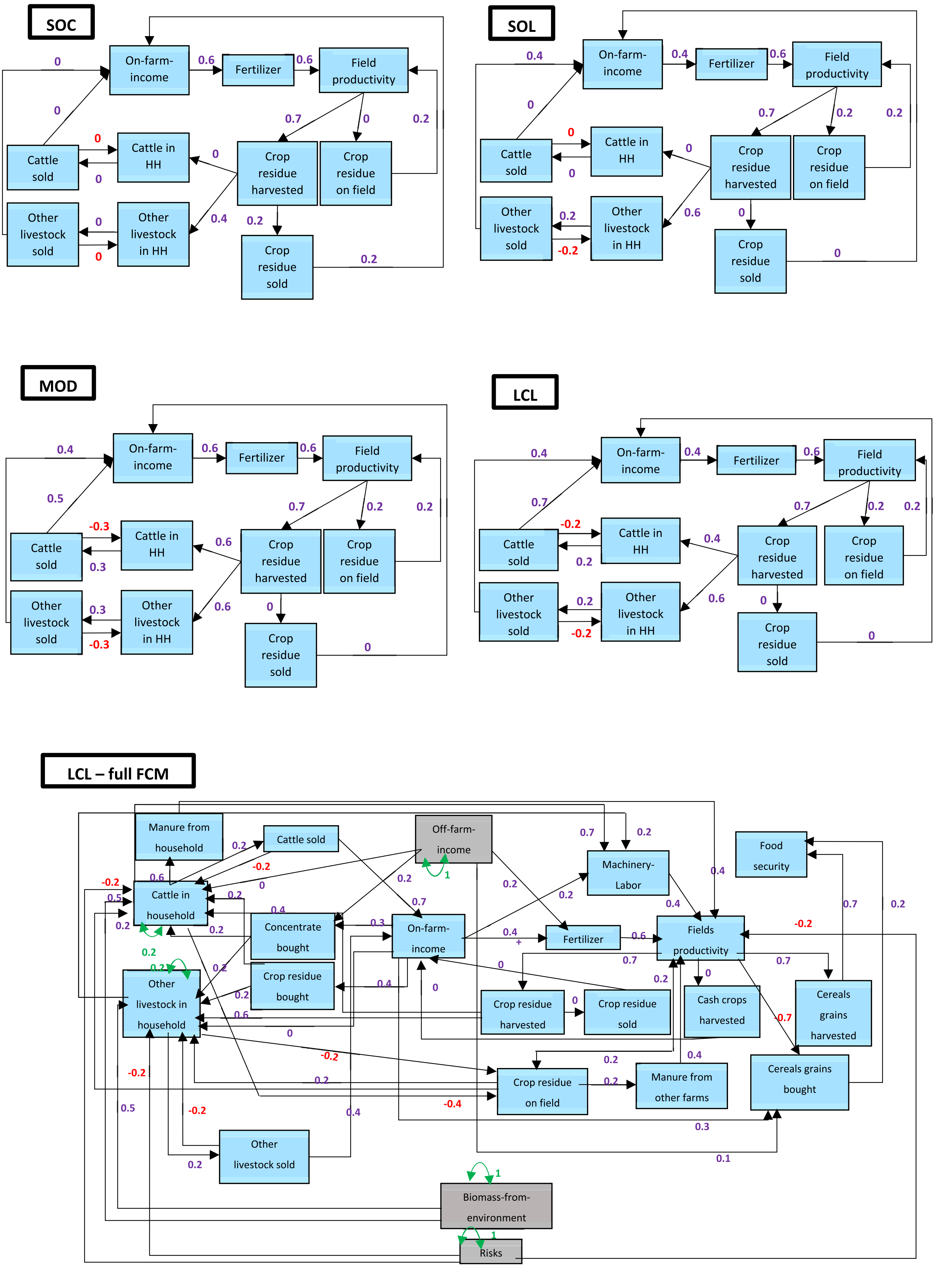
herd. Analogous variables were used by Ganeme et al. (2021) in a similar area in semi-arid Burkina Faso. In addition, they used small equipment which was also mentioned by farmers in the focus group discussions. Our participatory typology was oriented towards wealth and orientation in terms of crop and 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 (Fig. 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 Fig. 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).

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



(caption on next page)

Fig. 6. (SOC, SOL, MOD, LCL) Illustration of part of SOC, SOL, MOD and LCL FCM respectively, showing key differences between them. 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. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

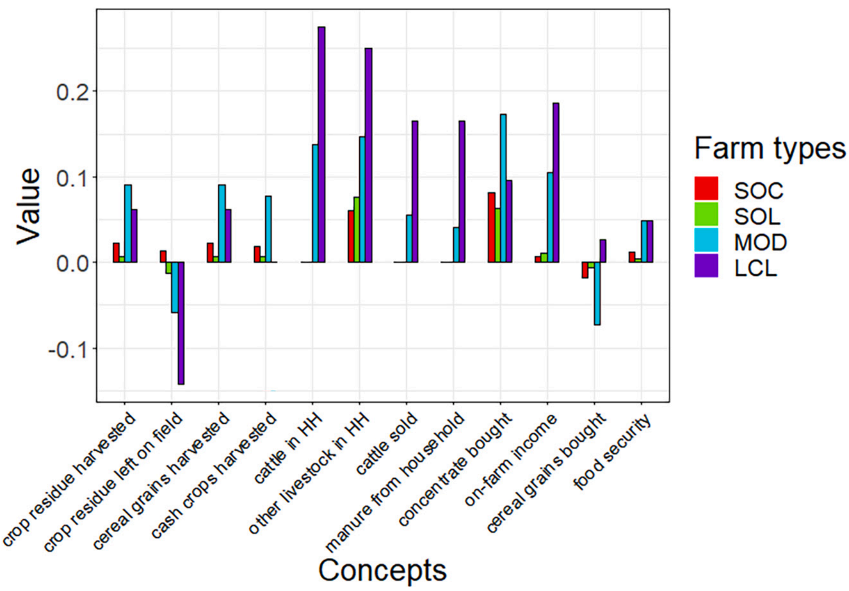


Fig. 7. Values of key concepts in the FCM for the baseline scenario per farm type. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock. HH = Household.

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 (Fig. 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 (Fig. 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., 2004). 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., 2022; 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., 2017). 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

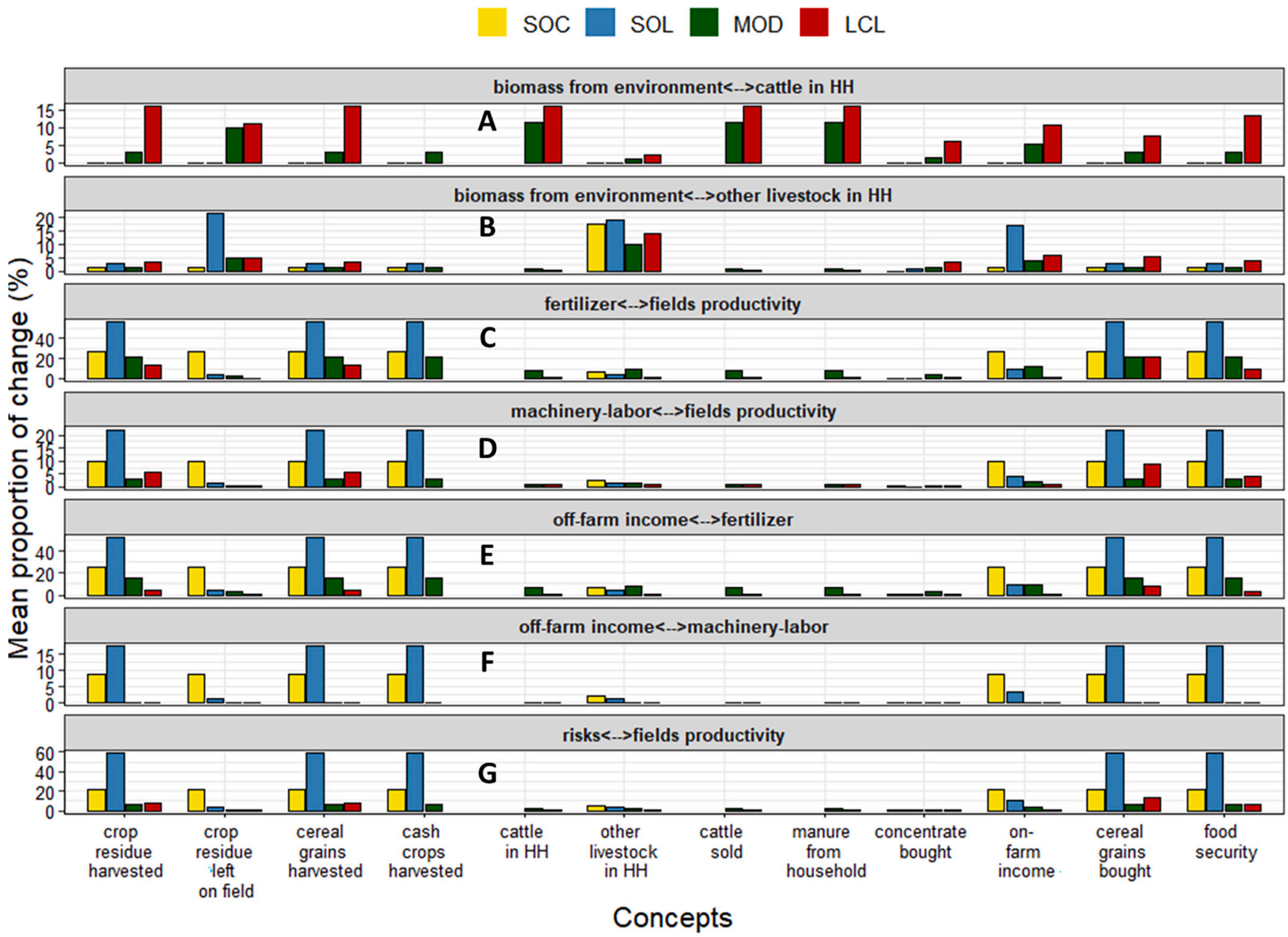


Fig. 8. results of sensitivity analysis showing mean proportion of change in concepts values as a result of variations of the most sensitive links all farm types have in common. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock. HH = Household.

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., 2022; 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).

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

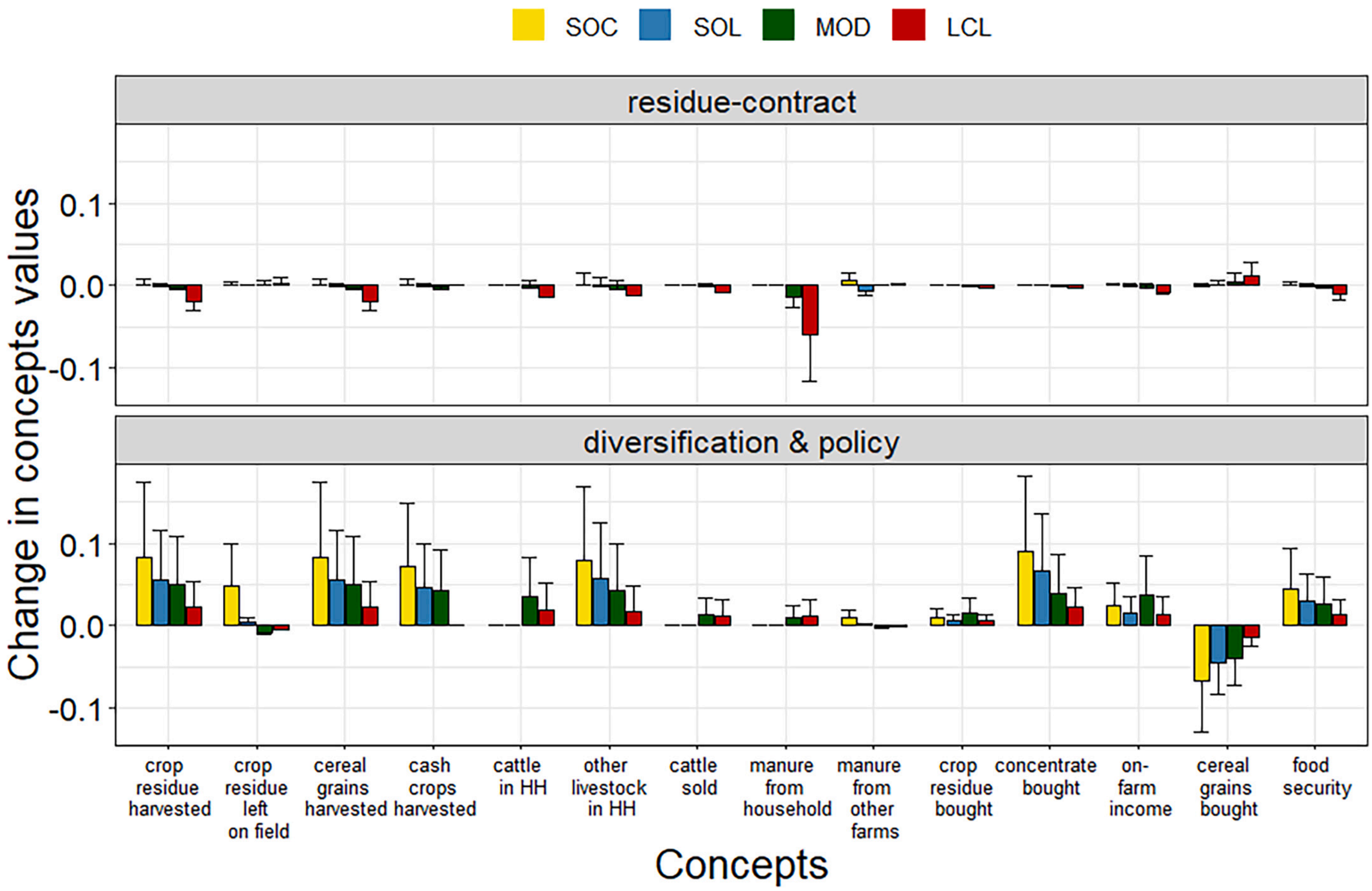


Fig. 9. Change of key concepts values as compared to the baseline for the 'residue-contract' and the 'diversification and policy' scenarios for all farm types. Error bars are standard deviations resulting from the variation in risks. SOC = subsistence-oriented crop, SOL = subsistence-oriented livestock, MOD = market-oriented diversified and LCL = land constrained livestock. HH = Household.

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.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2022.103458.

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