European Journal of Agronomy 151 (2023) 126983

Contents lists available at ScienceDirect

European Journal of Agronomy

journal homepage: www.elsevier.com/locate/eja

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

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ARTICLE INFO

Keywords:
Farming system
Crop-livestock
Biomass
Agro-ecology
Food security
Sub-Saharan Africa

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.

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https://doi.org/10.1016/j.eja.2023.126983
Received 23 December 2022; Received in revised form 13 September 2023; Accepted 17 September 2023
Available online 28 September 2023
1161-0301/

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, P. D, 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., 2016) 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., 2016; 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.

2. Materials and methods

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 ^{o}C (January) and 39 ^{o}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 Fig. S2 (supplementary materials). 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 (Fig. 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.

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 (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 1) for the monitoring of biomass production and management.

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,

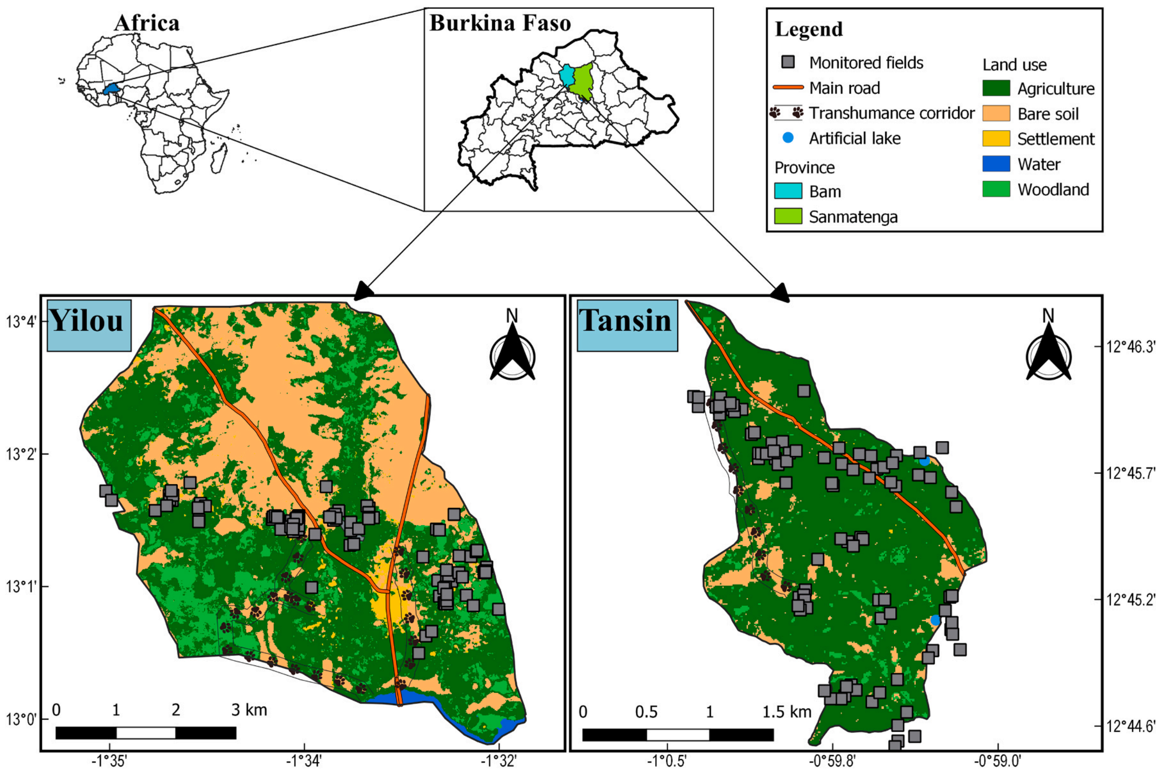

Fig. 1. Map of the study areas showing land use and monitored fields (87 and 90 fields in Yilou and Tansin respectively).

Table 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

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 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 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 2.3.1 to 2.3.3.

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.

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 (Fig. S2, supplementary materials). The results are analyzed in Section 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 (Fig. 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.

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 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 (Fig. S1, supplementary materials), 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.

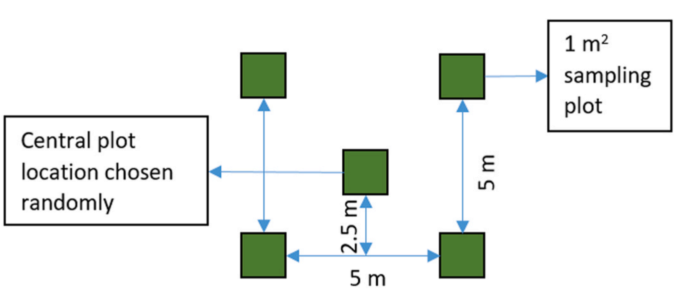

Fig. 2. Sampling framework used to measure the amount of crop residues remaining on the soil.

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.

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:

$$\mathrm{Nbal}_{\mathrm{fl}} = Ninput - Noutput \tag{1}$$

$$\mathrm{NUE}_{\mathrm{fl}} = \frac{Noutput}{Ninput} \tag{2}$$

Cropping system level:

$$\mathrm{Nbal}_{\mathrm{cs}} = \frac{\sum_{i=1}^{n} A_i (Ninput_i - Noutput_i)}{A_T} \tag{3}$$

$$NUE_{cs} = \frac{\sum_{i=1}^{n} A_i (Noutput_i)}{\sum_{i=1}^{n} A_i (Ninput_i)} \tag{4}$$

Where Ninput and Noutput are respectively the nitrogen input and output from a field in kg/ha. A_i is the area of the i^{th} field (in ha) while A_T is the total cultivated area by the farm (in ha). $\mathrm{Nbal}_{\mathrm{fl}}$ and $\mathrm{Nbal}_{\mathrm{cs}}$ 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.

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 Eqs. 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)

$$Small\quad ruminants\mathrm{ME} = \frac{0.315W^{0.75} + 0.048W}{k_m} \tag{5}$$

$$Cattle\quad and\quad donkey\mathrm{ME} = \frac{0.53(W/1.08)^{0.67} + 0.037W}{k_m} \tag{6}$$

$$\mathrm{k_m} = 0.35(ME_f/GE_f) + 0.503 \tag{7}$$

Metabolizable protein requirement (g/day)

$$Cattle, donkey\quad and\quad small\quad ruminants\quad \mathrm{MP} = 2.3W^{0.75} \tag{8}$$

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).

The gap between ME and MP required and directly provided by farmers to livestock was calculated at farm level (Eqs. 9 and 11) and per TLU (Eqs. 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 (3.4). However, the real contribution of pasture to livestock feeding was not measured.

$$\mathrm{FarmGapME, farm(\%)} : \frac{100(ME\quad required - ME\quad supplied)}{ME\quad required} \tag{9}$$

$$\mathrm{FarmGapME, TLU(MJ\ ME/TLU/day)} : \frac{ME\quad required - ME\quad supplied}{HerdSize} \tag{10}$$

$$\mathrm{FarmGapMP, farm(\%)} : \frac{100(MP\quad required - MP\quad supplied)}{MP\quad required} \tag{11}$$

$$\mathrm{FarmGapMP, TLU(g\ MP/TLU/day)} : \frac{MP\quad required - MP\quad supplied}{HerdSize} \tag{12}$$

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

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.

$$\mathrm{HHEnGap(\%)} : \frac{100(Energy\quad required - Energy\quad produced)}{Energy\quad required} \tag{13}$$

$$\mathrm{Energy\ required(kcal/year)} : DER\mathrm{x}365\mathrm{x}AE \tag{14}$$

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.

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. Results

3.1. Nutrient management at field and cropping system level

Nitrogen inputs in fields were generally smaller than the outputs (Fig. 3 A and Fig. 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 (Fig. 3 A), irrespective of the farm type and the cropping system (sole or intercropping) (p-value > 0.05 in all cases, tables S3 and S4 in supplementary materials). Similarly, cereal-legume intercropping did not affect the N balance at field level (Fig. 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/

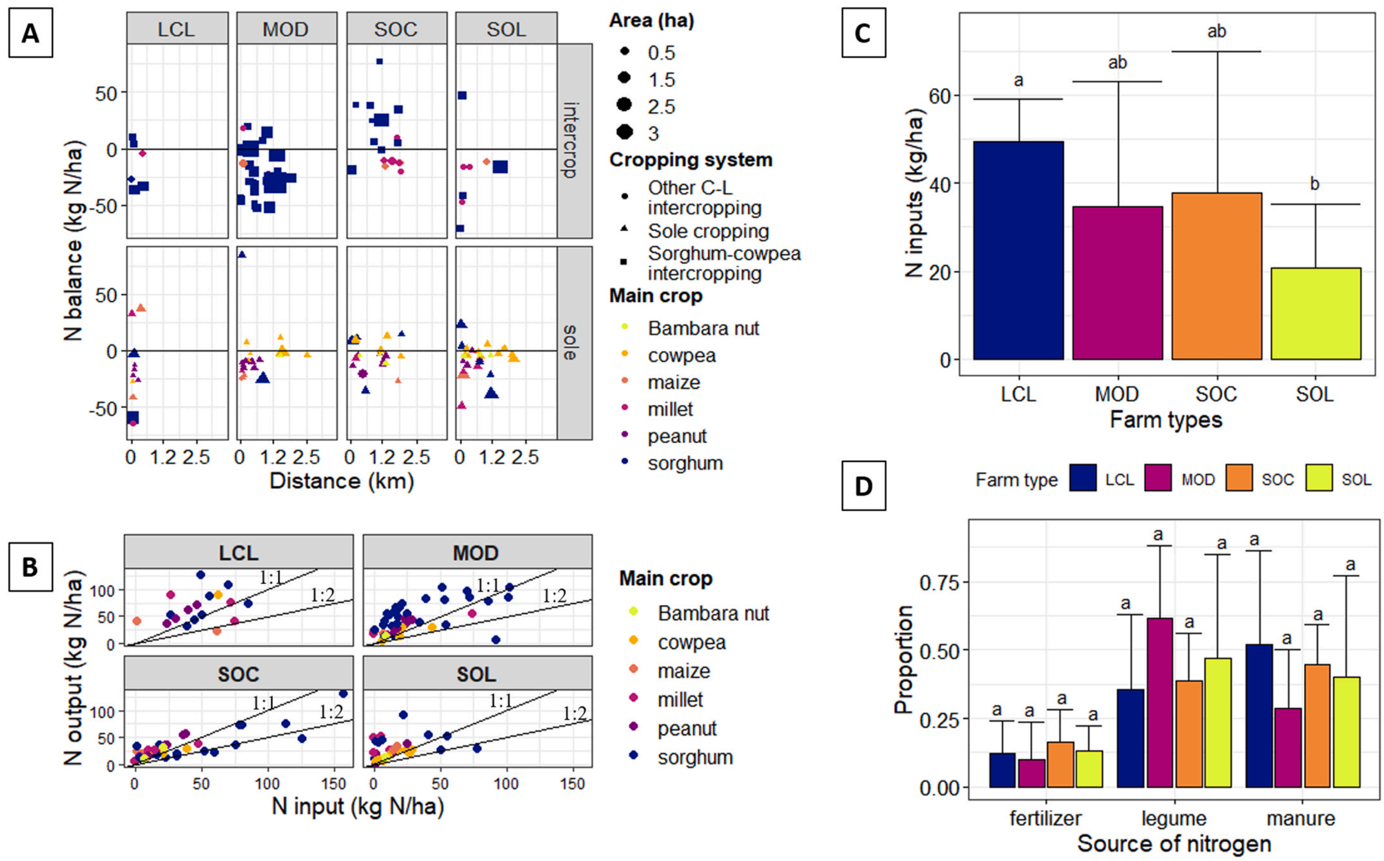

Fig. 3. (A) Nitrogen balance as function of distance of fields to households' settlement in intercropping and sole cropping. C-L = Cereal-Legume. (B) Field-level N output versus N input, with indication of nutrient mining (fields above the 1:1 line), low nutrient use efficiency (fields below the 1:2 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.

ha and 19 kg N/ha, p-value = 0.6) in general and across farm types (Fig. 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) (Fig. 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 (Fig. S2, supplementary materials). 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 (Fig. 3 C). The contributions of fertilizer, legume and manure to the total nitrogen (N) input at cropping system level were similar across all farm types (Fig. 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%) (Fig. 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 2). However, there was no significant difference in NUE across farm types.

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 (Fig. 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, 39–165 kg/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

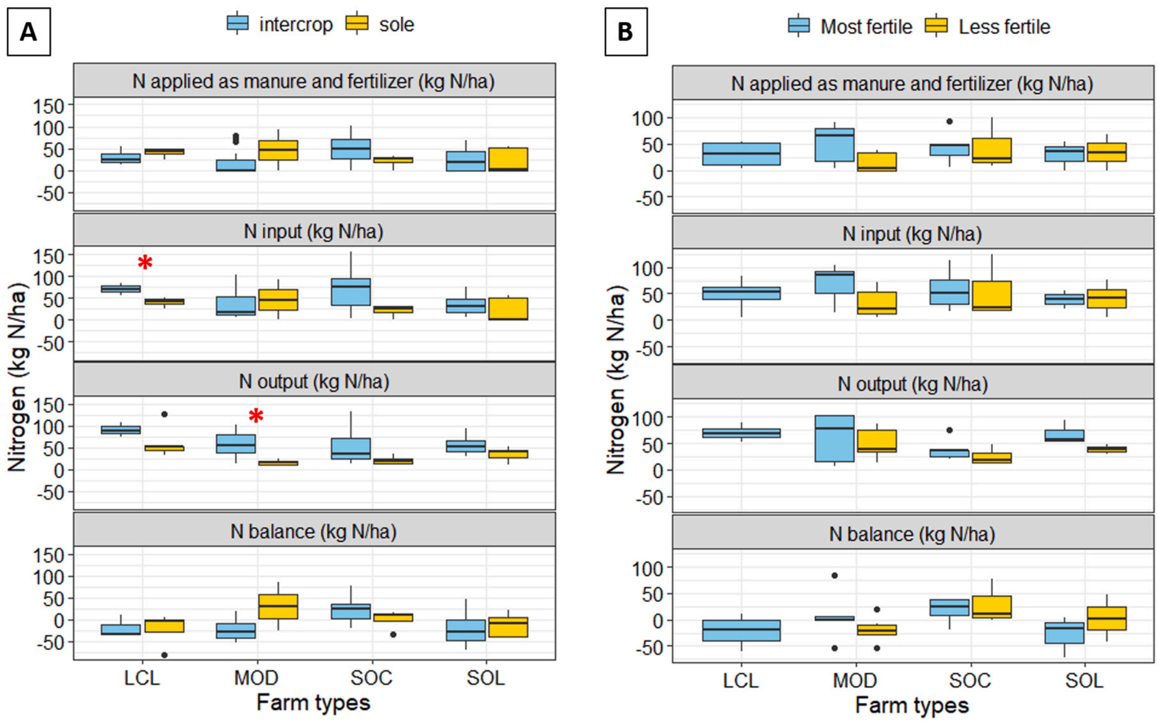

Fig. 4. (A) Nitrogen applied as manure and fertilizer, input, output and balance in sole cereals and intercropped cereal-legume fields. (B) Nitrogen applied as manure and fertilizer, input, output and balance in the most and least fertile sorghum fields according to farmers. Pairs of boxplots with a 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 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.

types. No peanut and cowpea residues were left on the soil by all farm types.

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 (Fig. 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

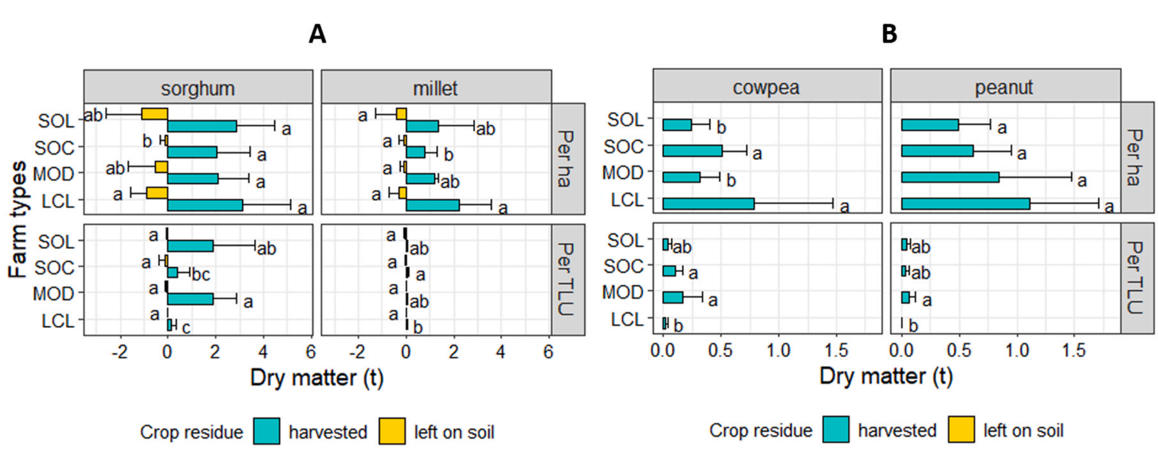

Fig. 5. mean amount of crop residues harvested and left on soil per ha and tropical livestock unit (TLU) for cereals (A) and legume crops (B). Error bars indicate the standard deviation and bars with the same letter are not statistically different. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

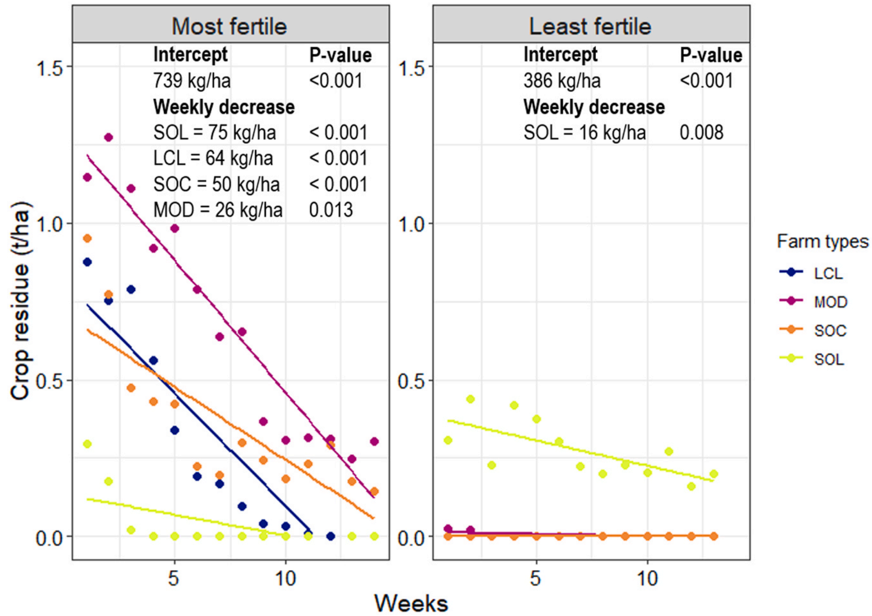

Fig. 6. Variation of sorghum residue left on soil in the most and least fertile fields. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

the fields.

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) (Fig. 7). At that time of abundant biomass availability, livestock feed requirements were mostly met through grazing, which is not depicted in Fig. 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 (Fig. 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). 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 (3.4). 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

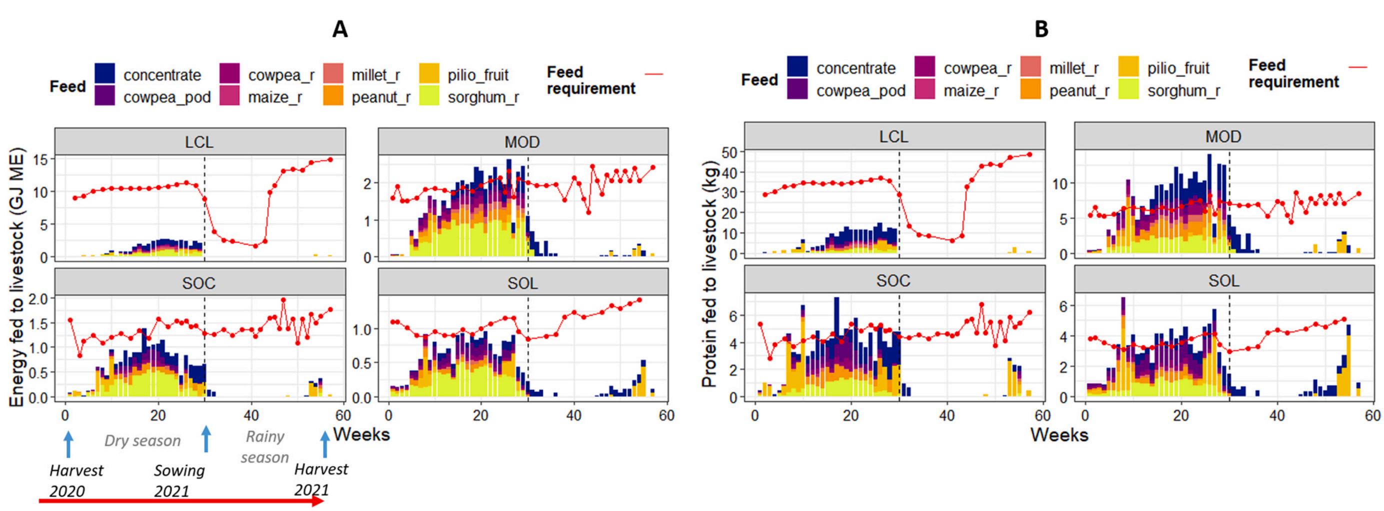

Fig. 7. Weekly average metabolizable energy (ME) (A) and protein (B) fed to the livestock herd throughout a year per farm type. The red line represent the feed requirement of the herd. Feed names ending with "_r" refer to crop residues, pilio_fruit = Piliostigma pods. The black dotted line is the limit 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
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.

(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 (Fig. 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). 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 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.

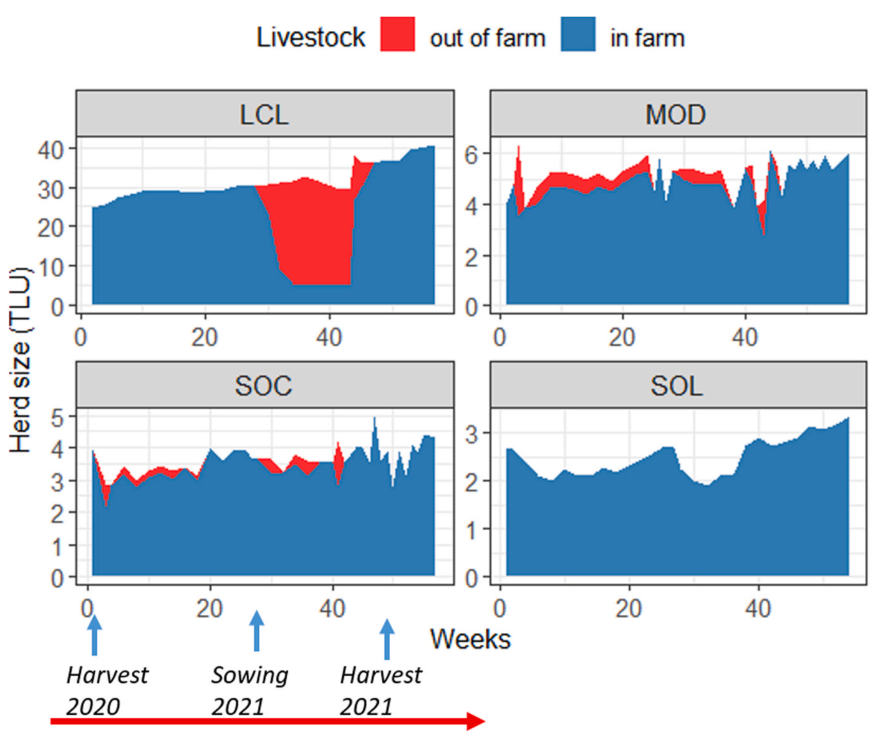

Fig. 8. herd size, consisting of animals within the village (blue) and out of the village (red) per farm type every two weeks. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

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 (Fig. 8). LCL farms practiced transhumance starting from the onset of the rainy season until the harvest period (Fig. 8 and Fig. 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 (Fig. 7 and Fig. 8). The herds of SOL farms, usually consisting only of small ruminants, were always kept on the farm and grazed within the village.

More livestock was sold than bought in all farms (Fig. 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%).

3.5. Food availability in households

The amount of energy produced by households was generally close or greater than their energy requirement (Fig. 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.

3.6. Biomass exchange between households

Biomass exchange occurred in all farm types (Fig. 11 A) 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 (0.5–35 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 (Fig. 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 2).

Sorghum residue exchange for manure (and vice versa) occurred only at the end of the dry season (Fig. 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

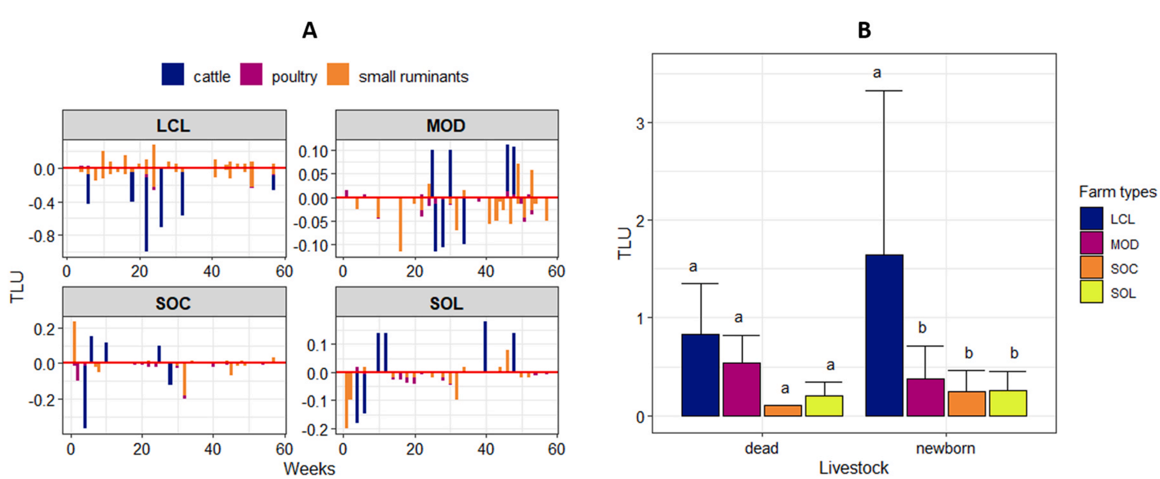

Fig. 9. Average tropical livestock units sold (negative values) and bought (positive values) by each farm type every two weeks (A). Average tropical livestock units newly born and dead per farm type (B). LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock. TLU = Tropical Livestock Unit.

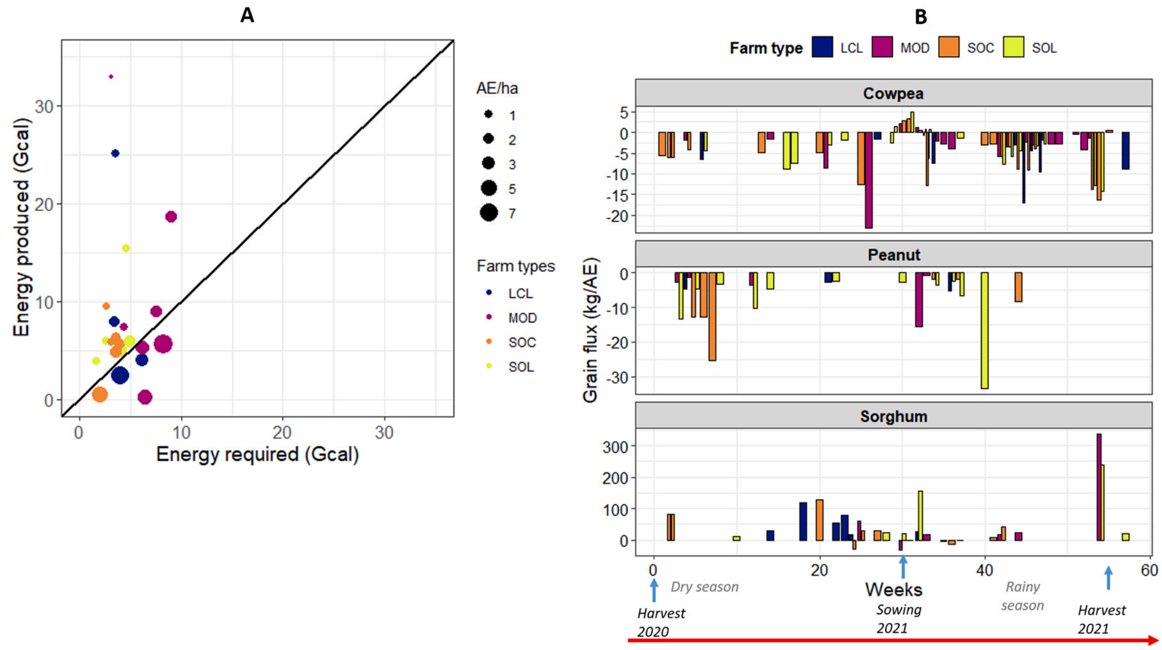

Fig. 10. Energy produced versus required in 2021 (A). The black line (A) is the first bisector. Weekly Inflow (positive values) and outflow (negative values) of grain in all monitored farms in 2020 and 2021 (B). Gcal = Giga calories. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

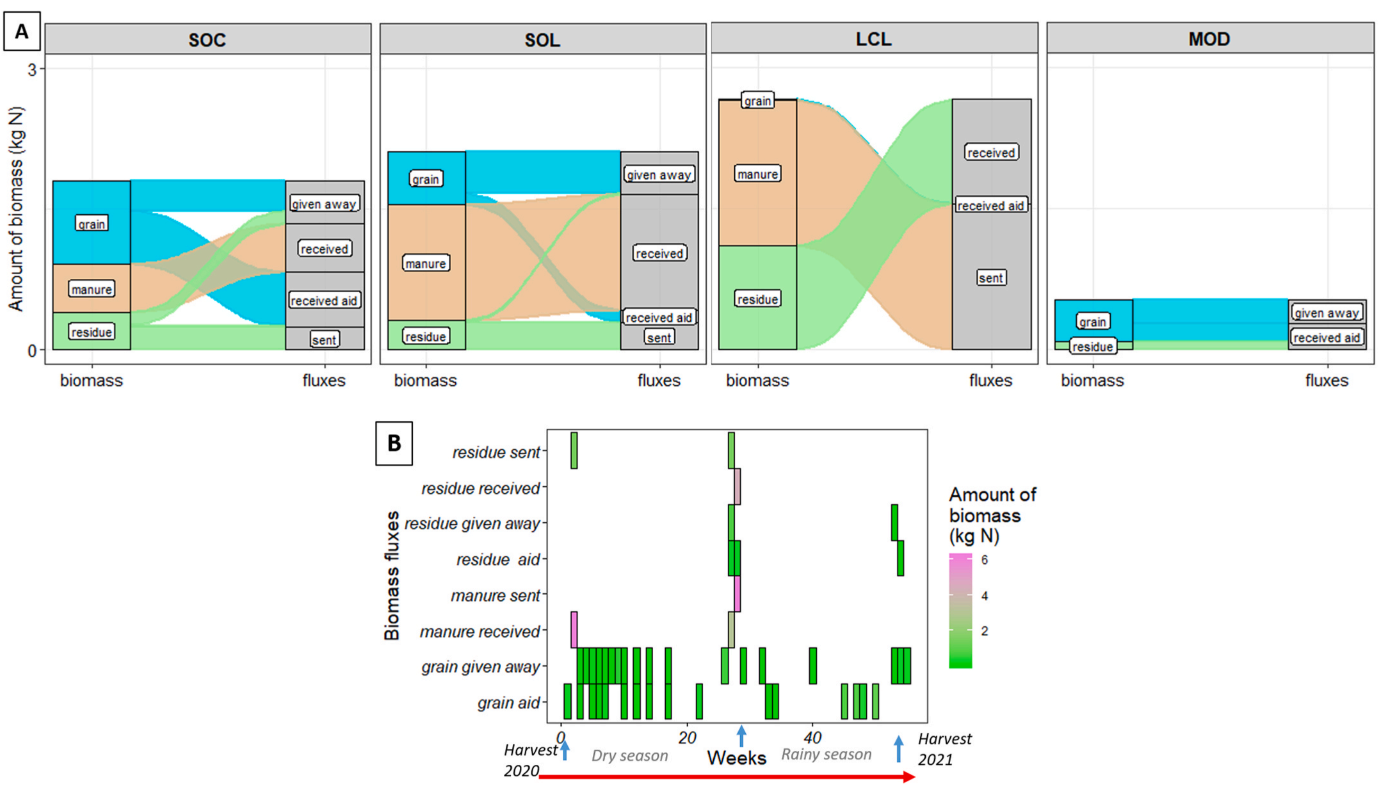

Fig. 11. (A) Average biomass exchange, expressed in kg of N per farm type over the whole period of study. (B) Weekly variation of biomass exchange between households. LCL = land constrained livestock; MOD = market-oriented and diversified; SOC = subsistence-oriented crop; SOL = subsistence-oriented livestock.

support the most vulnerable households occurred throughout the year and mainly during the dry season.

4. Discussion

Crop and livestock production in mixed crop-livestock systems in semi-arid Burkina Faso remains limited (Henderson et al., 2016). 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.

4.1. Can farmers feed their soil?

In general, N inputs (including legume fixation) for most fields were lower than 50 kg N/ha (Fig. 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., 2004). 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 soyabean 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 (Fig. 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.

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 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).

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. (2017) 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.

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.

CRediT authorship contribution statement

Gildas G. C. Assogba: Conceptualization, Data collection, Statistical analysis, Data curation, Formal analysis, Writing - review & editing. **David Berre:** Conceptualization, Writing – review & editing, Supervision. **Myriam Adam:** Conceptualization, Writing – review & editing, Supervision. **Katrien Descheemaeker:** Conceptualization, Writing – review & editing, Supervision.

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.

Data Availability

Data will be made available on request.

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.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.eja.2023.126983.

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