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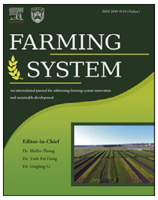

Biomass and nutrient flow dynamics and sustainability practices to de-risk environmental challenges in the sub-saharan Africa farming system

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ABSTRACT

In sub-Saharan Africa, productivity risks stem from weather variability, while environmental risks include soil nutrient depletion due to unsustainable farming practices that include monoculture, inadequate or lack of soil and water conservation measures, and low-nutrient application. As a result, shifts from the prevailing fallow system to permanent cultivation lead to soil degradation. The present study aimed to quantify the fluxes of biomass, nutrients, and nutrient balances from different fertilizer sources to de-risk the challenges related to agriculture and the environment in Mali. A farm household survey was conducted over two years (July 2018 to June 2020) with 45 households. The survey enabled us to categorize farm households into three typologies: high resource endowment (HRE), medium resource endowment (MRE), and low resource endowment (LRE). Data on sustainability indicators from cropland, livestock, farm input use, and redistribution units enabled the analysis of biomass and nutrient flow dynamics from households to farmlands and vice versa. The nutrient monitoring (NUTMON) tool generated nutrient flows and balances. Results showed that the total annual biomass collected per hectare by HRE (22.3t) is significantly higher than that collected by MRE (13.4t) and LRE (5.35t) farms ($P < 0.001$). Compared to LRE (10.3 t ha^{-1} $year^{-1}$), HRE and MRE farmers produced six times (60 t ha^{-1} $year^{-1}$) and three times (34 t ha^{-1} $year^{-1}$) more manure, respectively. Farm households with better endowment status observed a higher rate of nutrient utilization. For the major crops, nutrient application rates of HRE farms in kg ha^{-1} (cotton: 12.6 N, 4.2 P, 18.2 K) and (maize: 9.18 N, 2.34 P, 10.7 K) were significantly higher than that of MRE and LRE farms ($P < 0.01$). The study confirms that household endowment status determines farmlands' nutrient flows and fertility levels. Quantifying biomass transport and understanding nutrient flow dynamics enable the derivation of context-specific solutions to reduce risks associated with productivity and the environment.

1. Introduction

West Africa's population is one of the fastest growing in the world, with a growth rate of 2.64% per year (https://worldpopulationreview.com). The population of Mali, a landlocked country in West Africa, increased from 8.5 Million in 1990 to approximately 23 Million in 2023 and is expected to reach 44 Million by 2050 (https://data.worldbank.org). The increase in population exerts pressure on water, land, and other natural resources, risking environmental sustainability. Environmental risks are associated with continually mining soil nutrients from farm fields due to unsustainable farming practices that include monoculture, inadequate or lack of soil and water conservation measures, and low-nutrient applications (Sanogo et al., 2023). Moreover, agricultural productivity risks arise from variabilities in weather patterns, such as unpredictable and unreliable rainfall, temperature variations, and emerging pests and diseases (Huet et al., 2022; Bizo et al., 2024).

In southern Mali, where 80% of the agricultural land is already under low mineral fertilizer use and widespread mixed crop-livestock systems exist, shifts from the prevailing fallow system to permanent cultivation have led to poor soil fertility and land degradation. The decline in nutrient status during cultivation is an inevitable consequence of clearing and a long-term reduction in the diversity of the natural vegetation, which is reinforced by the effects of cultivation (Feller and Beare, 1997). In these conditions, soil fertility is continuously reduced by the exportation of plant biomass from the farms by both farmers (harvesting crop

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products and crop residues) and herders (free grazing of crop residues by cattle). This decline in fertility is compounded by the natural mineralization of soil organic matter (Dongmo et al., 2012).

The pastoral system in Mali is based on livestock grazing, which is regarded as one of the leading causes of land degradation (Ayantunde et al., 2014; Umutoni et al., 2016). With the increased livestock density and the privatization of agro-pastoral resources (La Rovere et al., 2005), crop residues, which are typically used as mulching to improve soil fertility and reduce farm-level erosion, are now removed by most farmers, and stored to feed cattle during the dry season (Barbier et al., 2009). Thus, crop residues returned to cropland are usually low.

In Mali, farming is a low-input system characterized by limited resources, low technology, low funds, and limited information (Kaya et al., 2000). Cotton (*Gossypium hirsutum* L.) is the main cash crop. It is often grown in rotation alongside cereals such as sorghum (*Sorghum bicolor* (L.) Moench), millet (pearl millet (*Pennisetum glaucum* (L.) R. Br.), maize (*Zea mays* L.), as well as legumes such as groundnut (*Arachis hypogaea* L.), and cowpea (*Vigna unguiculata* (L.) Walp.). Cotton and maize are the major crops in the region that receive nutrient input additions in the form of manure and mineral fertilizer, whereas other cereal crops rarely receive fertilizer (Autfray et al., 2012; Traore et al., 2014, 2017). These practices eventually contribute to the nutrient depletion of the low-fertile soils in the farm fields. Soil fertility depletion is a risk for both productivity and the environment. It negatively affects up to 40% of the annual agricultural revenue of farmers in southern Mali (De Ridder et al., 2004). To reverse this trend, farmers practice collecting and storing biomass not only for use as animal feed but also to produce organic manure (Blanchard, 2010). Crop residues are the most abundant and available organic resources, and their retention in croplands can play a significant role (Falconnier et al., 2023). A nutrient flow from biomass, organic household waste, compost, and animal manure to crop fields is a sustainable practice in soil fertility management and improves agricultural productivity. However, studies have shown negative nutrient balances in the ferruginous tropical soils located in the subhumid zone of west Africa (Audouin et al., 2015). In southern Mali, nitrogen (N) and potassium (K) balances were reported negative (-27 to -34 kg ha^{-1} N, -18 to -28 kg ha^{-1} K), while P content was close to zero (Cobo et al., 2010; Bationo et al., 2012). Despite the promising results regarding crop biomass and soil fertility management (Autfray et al., 2012), there is a critical knowledge gap on nutrient flow dynamics from households to farm fields and vice versa, particularly for farms with different levels of resource ownership. The dynamics and deficiencies in farm-level nutrients for the key crops can be better understood by quantifying biomass transport and organic inputs under different farm typologies. In the study area, farmers generally produce crops in fields located within an 8 km radius of their homesteads. To avoid conflicts due to free grazing or from transhumance practices, farmers prefer to collect, transport, and store biomass close to their households to ensure safety and long-term use. The study focused on quantification of seasonal biomass transport and nutrient flows under different levels of farm ownership. This is a crucial step in farm level fertility management. The study's hypothesis is that farm household endowment status determines differences in biomass and organic movement and stocks. Understanding the differences in organic input management among farm typologies enables the tailoring of agricultural advice and effective prioritization of actions to promote sustainable and productive farming systems. Therefore, the objective of this study was to characterize the dynamics of nutrient flows from biomass collected and transported from farms to households, as well as monitor and quantify organic inputs (farmyard, compost, and cattle manure) obtained by different farm typologies in different seasons. The methodology included experimentation on biomass and nutrient flows and laboratory analysis to quantify nutrients (N, P, K) availability in the organic inputs. Nutrient monitoring for tropical farming systems (Nutmon) tool was applied to evaluate nutrient flows under different farm typologies and to determine the nutrient balance for each farm typology and crop type.

2. Materials and methods

2.1. Study site

The study was conducted in three different villages of the Koutiala region in southern Mali, Zansoni (12.61 N, 5.57 W), Sirakélé (12.51 N, 5.47 W), and N'golonianasso (12.72 N, 6.16 W) (Fig. 1). The selected villages are in the Sudano-Sahelian agro-climatic zone. In April, the mean maximum temperature peaks at 40 °C, making it the hottest month of the year. In contrast, August experiences a relatively lower mean temperature, with an average maximum of 30 °C (Fig. 2). The onset of the rainy season commences in May, signalling the beginning of increased rainfall. Over the following months, rainfall steadily increases, reaching its peak during July and August. Subsequently, as the season progresses, there is a gradual decline in rainfall, which aligns with the seasonal dynamics observed in the region (Traore et al., 2013). The climate is characterized by three seasons: the rainy season, from June to October, followed by the cold season, which extends from November to February and is marked by post-harvest activities such as transporting biomass from the fields to households for storage. From March to May, the dry season is mainly characterized by the intensification of biomass transformation into manure, often including mixing with animal faeces. The landscape of the study area consists of a rocky plateau and low plains with slight slopes, while the soils are ferruginous tropical soils, which are mainly Alfisols and Ultisols and makeup 40% of the soil types in the subhumid zone of West Africa. Soil fertility and fertility gradients vary among the fields with the highest amounts of nutrients close to the villages. The soil texture is loamy-sandy with 59.7% sand, 26.14% silt, and 14.1% clay in the 0–20 cm soil layer. The soil is highly acidic, with a pH value of 4.64. The organic carbon content in the soil is 1.46%, while the N, P, and K contents are 0.19%, 0.01%, and 0.35%, respectively (Supplementary I).

Livestock represents a vital component of the mixed farming system in the region. It is characterized by keeping cattle, sheep, and goats in combination with cultivating crops. Crop residues, as well as pasture and forage crops that grow on fallow and communal lands, often act as feed resources for the animals in crop-livestock system (Falconnier et al., 2015; Umutoni et al., 2015; Guindo et al., 2022).

The largest share of the cultivated land is allocated to the production of sorghum, millet, and maize, usually grown in a two-to three-year rotation with cotton. Farm types are divided into three groups based on the number of cattle and farm equipment. Large farms are better endowed with production resources but account for only 6%–13%, with a mean cropped land of 18 ha, a household size of 34, 6 draft oxen, and herd size of 41, while medium-sized farms are the most widespread, ranging from 69% to 81%, with a cropped area of 10 ha and with a household size of 16, 3 draft oxen, and a herd size of 8. Small farms vary from 9% to 12%, with a mean cropped land of 8 ha and household size of 4 and with one animal in all. With the availability of resources, particularly cattle, owners of large and medium-sized farms can intensify their cotton and cereal production and diversify farm level activities (Blanchard, 2010).

The Compagnie Malienne pour le Développement des Textiles (CMDT) usually subsidizes inputs such as seed, fertilizer, and pesticides to produce cotton and maize. Millet and sorghum fields seldom receive mineral fertilizer inputs or manure. Crop yields differ under the different farm typologies. The mean cotton yield varies from 1082 kg to 998 kg for large and medium farms, respectively, compared to 752 kg for small farms. Average maize yields were 2242 kg ha^{-1}, 1380 kg ha^{-1}, and 984 kg ha^{-1} respectively, for large, medium, and small farms. Regarding millet/sorghum, the mean yields were 926 kg ha^{-1} and 703 kg ha^{-1} for large farms and medium farms respectively compared to 648 kg ha^{-1} for small farms (Djouara et al., 2006; Traore et al., 2015). Crop diversification, including intercropping, in this region reduces the risk of crop failure for smallholder farmers by improving productivity per unit of land compared to the sole cropping system (Sogoba et al., 2020).

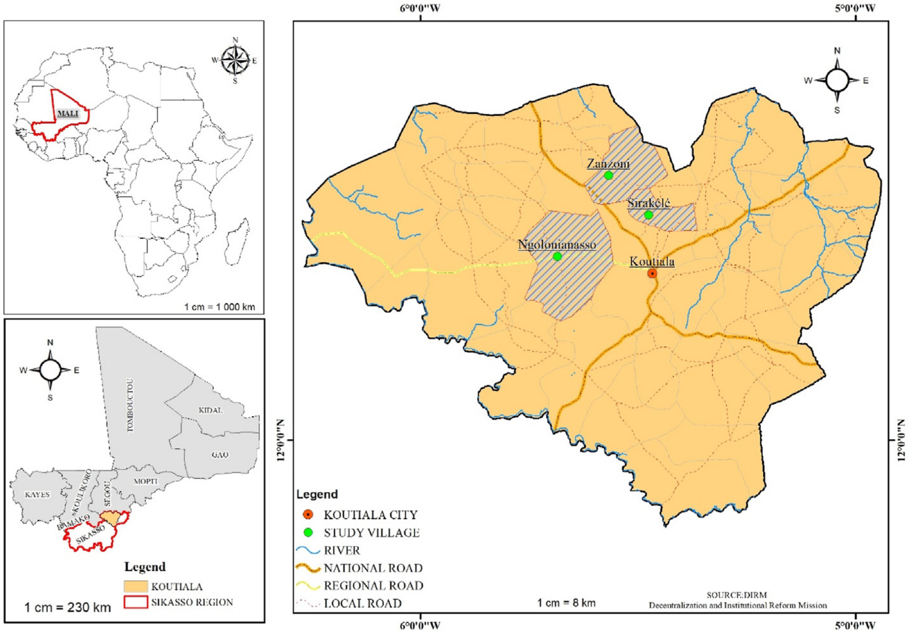


Fig. 1. Study site in the Koutiala region of southern Mali.

2.2. *Farmer selection*

A total of 45 farmers in Zansoni, Sirakélé, and N'Golonianasso villages in the Koutiala region of southern Mali were selected for the study. The selection was performed using a linear systematic random sampling method (R = N/n) on a random starting point and a fixed periodic interval. R represents the sampling interval calculated by dividing the total number of farms (N) by 15, representing the desired sample size (n) per village. The farmers were then divided into three main farming typologies based on the production system, as described by Falconnier et al. (2016) and De Ridder et al. (2015). The farm household typologies are:

1. High Resource Endowment (HRE) farms are characterized by draft oxen greater than four, a herd size >20, more than 20 ha of cropland, and more than 20 workers.
2. Medium Resource Endowment (MRE) farms, with up to four draft oxen, a herd size of five to 20 with cropland of 10–15 ha, and 10 to 20 workers.
3. Low Resource Endowment (LRE) farms, with up to two draft oxen, a herd size of one to five, and cropland of one to 10 ha.

For the survey, 14 farm households were categorized under the HRE and 19 under the MRE, whereas 12 farm households fell within the LRE category.

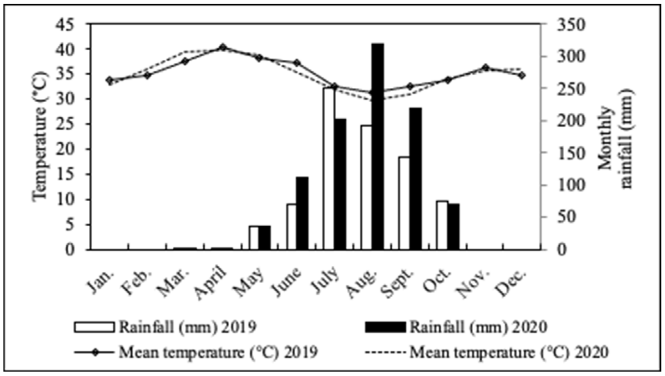


Fig. 2. Seasonal rainfall and temperature for 2019 and 2020 in the Koutiala region of southern Mali.

2.3. *Data collection and analysis*

Data were collected through a baseline survey starting with an inventory construction and the continuous monitoring of the resources of 45 farm households from July 2018 to June 2020 (Supplementary II and III). Information was recorded for each farm household according to the characteristics of the farm, such as household size (male, female, in-house workers), crop yield and biomass, cropland, agricultural equipment (cart, plough), animals, manure types, and sources, poultry, chemical inputs, and seeds. The approach was based on individual interviews with heads of households using data collection sheets (Supplementary II and III).

Surveys were performed every three months to capture within-household dynamics about the farmers' fields. The period from July to September corresponds to the establishment, growth, and crop-development phase while harvesting, biomass storage, and manure production activities characterize the period from October to December and from January to March. April to June corresponds to the transition between biomass storage (October–March) and the growing period, characterized by fodder scarcity and manure transportation to fields.

Crops monitored include cotton (cv NTA_MS334 and BRS 293), maize (cv Sotubaka and Dembagnuma), millet (cv Souna), and sorghum (cv Keniguéblé, Tièkadon, Tiandougou, and CSM63). Crop fields were monitored continuously every three months for two years (July 2018 to June 2020), spanning a full biannual rotation (cotton-millet/sorghum, maize-millet/sorghum, millet/sorghum-cotton, millet/sorghum-maize, etc.). A spring scale with a capacity of 100 kg was used to determine the weight of one cart of biomass for each residue type (cotton, maize, millet, sorghum) and manure type, including farmyard manure (household waste and dead leaves collected daily), compost, and cattle manure (animal droppings) in all fields. The weights obtained from the cartloads were used to compute the total biomass produced and manure transported to the fields.

Biomass was quantified from October to March each year, while manure (farmyard, compost, and cattle manure) was weighed regularly (every three months) to track the evolution of stocks. Grain and biomass yields were determined by analyzing a plot size of 25 m^2 on each of 0.5 ha (Supplementary IV). About 2 kg of fresh biomass was placed in an oven and dried at 70 °C for 48 h to determine the total dry biomass yield per hectare.

The mineral outflow coefficients recorded per crop (cotton, maize, millet, and sorghum) in the literature were used to quantify the biomass nutrient contents (Kanté, 2001; Bationo et al., 2015). Periodic biomass and manure quantification was conducted in collaboration with farmers. In May and June, a second quantification of manure brought to the fields was performed to determine any losses or other external inputs of manure (purchases, gifts, etc.). The nutrient contents in the biomass and various manure sources (farmyard, compost, and cattle manure) were analyzed at the soil laboratory of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in Sadoré (Niger) (Supplementary V). The manure dose was determined by dividing the quantity of manure in tons by the number of hectares for each farm typology. Based on farm types and livestock (cattle, sheep, goats, and donkeys) number, annual forage requirements were calculated according to standards of 900 kg year^{-1} (cattle), 150 kg per head year^{-1} for small ruminants (sheep, goats), and 720 kg year^{-1} (donkeys) (Blanchard, 2010).

Soil samples were collected from the top 20 cm, using an auger at five points along the diagonal in each plot during May each year before the onset of the rainy season. These five soil sub-samples were pooled to obtain 1 kg of composite sample for laboratory analysis. The soil analyses comprised of the soil pH, % P (Bray-I), total % nitrogen, and % soil organic carbon (SOC) (Nelson and Sommers, 1996). The available % K in the soil was extracted with 1 M NH$_4$OACc solution (Helmke and Sparks, 1996) and determined by flame photometry, while the soil granulometry was determined by the sedimentation method (Taubner et al., 2009). The collected data for each farm typology were entered into the database under the “Nutmon” framework (www.nutmon.org) (Smalling, 1993; Ehabe et al., 2010). The Nutmon framework is a methodology for monitoring and budgeting nutrient flows in tropical farming systems and has been used successfully in India, Vietnam, Indonesia, Kenya, Uganda, Ethiopia, Burkina Faso, Nigeria, and Ghana (Gachimbi et al., 2005; Phong et al., 2011; Surendran et al., 2016). Nutmon framework enables the assessment of trends based on the local knowledge on soil fertility management. The database entry in the framework was followed by data processing where the Nutmon tool generates flows and balances. In this study, we focused on measurable flows given per farm and crop, such as mineral fertilizer flows (IN1: NPK and urea), organic manure flows (IN2: compost, farmyard manure, and cattle manure), and grain and biomass output flows (OUTPUT1 and OUTPUT2, respectively). However, we did not account for air deposition (IN3), biological nitrogen fixation (IN4), or sedimentation (IN5). We also did not consider outputs such as leaching (OUT3), gaseous losses (OUT4), or erosion (OUT5). The nutrient supply for NPK (14-22-12 for cotton and 16-16-16 for cereals and urea (46% N) at farm scale and field data for each crop (cotton, maize, millet, and sorghum) was entered into the “Nutmon” model to generate nutrient partial balances by farm typology. The balances at the field scale were generated in kg per hectare for each crop. To switch from field to the farm scale, we summed the amount of each nutrient (e g: Nitrogen) of all the crops generated from the Nutmon model (kg ha^{-1}) for each farm typology.

2.4. *Statistical analysis*

Descriptive statistics (means and standard deviations) were used to analyze the mean distributions within and among farm typologies. Analysis of variance (ANOVA) was carried out using Genstat software 18th edition, while the Student-Newman and Keuls test at the 5% significance level ($P < 0.05$) was used to conduct pairwise comparisons. The biomass flow was established using the flowchart designer.

3. Results

3.1. *Farm characterization*

About 31% of the total farms evaluated were HRE farms, 42% were MRE farms, and 27% were LRE farms (Table 1). The household size, number of workers, herd size, and cropped land varied substantially ($P < 0.001$) from one farm typology to another (Table 1). The herd size was 16 and 11 for HRE and MRE respectively compared to 5 for LRE. In this system, livestock belongs to the crop-livestock farmer and is generally under the responsibility of a care giver who takes care of their feeding and watering. The total cropped land for HRE farms (20 ha) was two times greater than MRE farms (11 ha) and three times greater than LRE farms (6 ha) (Table 1). The mean crop land for cotton and millet was 5 ha in HRE farms, 3 ha in MRE, and 2 ha in LRE farms (Figs. 3–5). The farm fields were located within an 8 km radius around the villages. The quantity of manure obtained from different sources as per the characterized farms is presented in Table 2, similarly quantity of biomass collected seasonally is presented in Table 3. The total annual biomass is provided in Table 4.

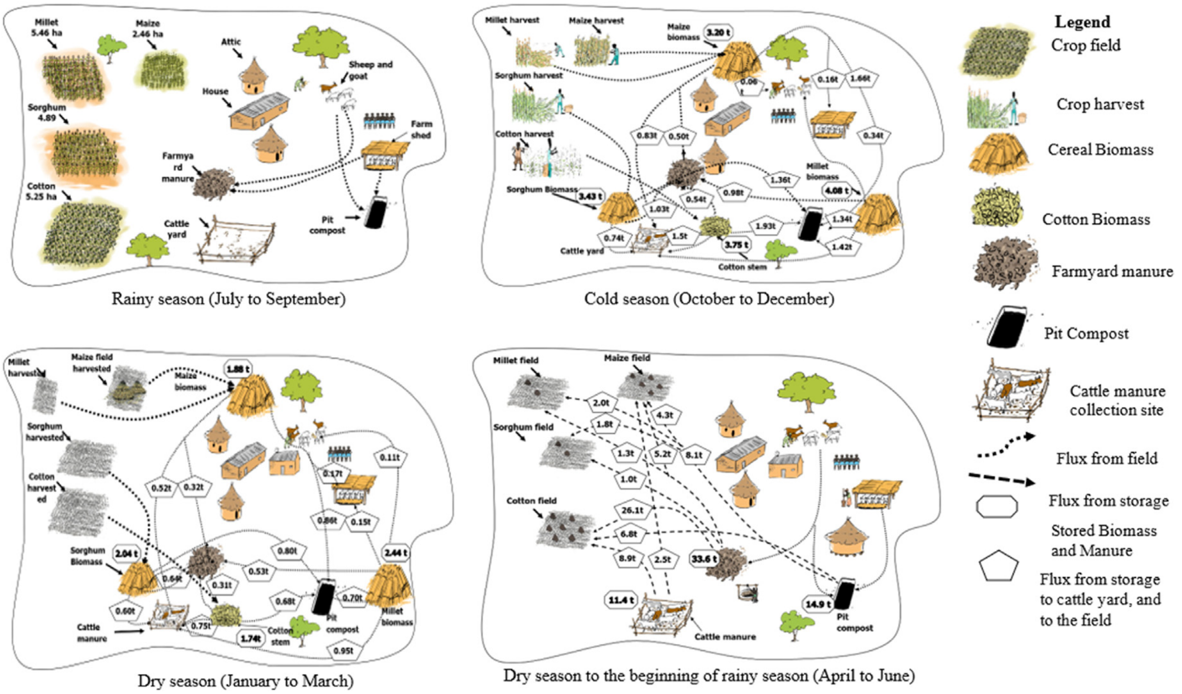
3.2. *Quantitative analyses of total biomass and organic inputs in each farm typology*

Regardless of the types of organic inputs (farmyard, compost, and cattle manure), the application doses on farm fields for different crops did not vary among the farm typologies. However, they varied significantly depending on the organic input type (Table 4). The total annual biomass collected by HRE (22.3 t year^{-1}) is significantly higher than that collected by MRE ($P < 0.001$), and LRE ($P < 0.001$) (Table 4). HRE and MRE households are able to produce 60 t year^{-1} and 34 t year^{-1} of manure, compared to 10.3 tyear^{-1} produced by LRE households. A higher proportion of planted area is used to produce organic inputs in MRE and LRE households (35% and 21%, respectively), compared to HRE (15%). Based on fodder needs for herd of each farm typology (Table 1) and deducting the biomass required for compost preparation (Table 2), the total yearly available biomass was 13.14t, 8.76t, and 3.72t for HRE, MRE,

Table 1
Farm characterization standards.

Typology	Population (Nr[a])	Workers (Nr)	Plows (Nr)	Carts (Nr)	Seed drills (Nr)	Cattle (Nr)	Sheep (Nr)	Goats (Nr)	Donkey (Nr)	Land (ha)
HRE	30.6	21.7	2.92	2	1.57	20.8	16.9	22.6	4.64	19.9
MRE	19.95	13.4	2.21	1.53	1	19.4	7.2	15.2	3.58	10.9
LRE	13.9	9	1.5	1.08	0.5	4.5	3.8	10	1.92	6.4
Mean	21.7	14.8	2.24	1.55	1.04	15.9	9.3	16.1	3.47	12.4
F.Prob.	<0.001	<0.001	<0.001	0.001	<0.001	<0.001	<0.001	0.01	0	<0.001
SED	2.96	1.8	0.31	0.23	0.22	3.32	2.81	3.81	0.73	1.37

[a] Nr = number. NB: Assets per holding = 0.25 * (household members aged under 10) + 0.5 * (household members aged 11 to 14) + 1 * (household members aged 15 to 54) + 0.5 * (household members aged 55 to 65) + 0.25 * (household members aged over 65). HRE: High Resource Endowment; MRE: Medium Resource Endowment; LRE: Low Resource Endowment; SED: Standart Error of Difference of the mean.



Rainy season (July to September)

Cold season (October to December)

Dry season (January to March)

Dry season to the beginning of rainy season (April to June)

Fig. 3. Biomass and manure flows per period for HRE farms.

and LRE farms, respectively. This available biomass was much lower than the potential requirement for livestock feed (refer the annual forage requirement by livestock presented in section 2.3), estimated at 28.5, 23.2, and 8.04 t for HRE, MRE, and LRE farms in a year, respectively.

In the HRE farms, the application dose for farmyard manure was 1.69 t ha^{-1} compared to the 0.71 and 0.58 t doses observed for compost and cattle manure respectively. The total annual organic inputs differed significantly among the farm typologies ($P < 0.001$). If the organic inputs were applied to all crops per hectare, HRE and MRE plots would receive approximately 3 t, while LRE plots would receive 1.6 t (Table 4). In practice, we found that the HRE and MRE farms mainly focused on cotton and maize fertilization by applying 3 to 6 t ha^{-1} of organic inputs compared to 1 t applied for millet and sorghum. In contrast, the LRE farms did not exceed applications of 3 t ha^{-1} for cotton and applied only 0.5 t ha^{-1}organic inputs to millet and sorghum.

3.3. Seasonal biomass and organic input flows

The biomass and organic input flows varied over the different periods within each year for the three farm typologies (Figs. 3–5). In the rainy season (July–September), the biomass and organic input flows were low for all farm typologies, but the organic input stocks increased as the rainy season progressed. Over the two years (2019 and 2020) on average, organic input flows for farmyard manure, compost, and cattle manure in HRE farms were 9.5 4.9, and 3.7 t at the end of September, respectively. The corresponding figures during the same period for MRE farms were 7.6, 2.8, and 2.4 t respectively. Similarly, the organic input flows for LRE farms were 3.6t (farmyard manure), 0.36t (compost), and none (cattle manure). While the highest organic flows were recorded during January to March, April to June represented a season with low organic input flows (Table 2). For biomass transport, October to December represent a season with the highest biomass transport in both years (2019 and 2020) with the corresponding figures of HRE (14.2 t), MRE (8.62 t), and LRE (3.51 t). The mean annual biomass transported in HRE farms (5.89 t) was significantly higher than that of MRE and LRE farms ($P < 0.001$) (Table 3). Biomass storage for the three farm typologies was below one ton per hectare from April to June, a period primarily dedicated for transportation of organic inputs to farm fields (Figs. 3–5, Table 3). While HRE households utilized the highest biomass compared to MRE and LRE households (Figs. 3–5), organic input production from January to March is significantly higher ($P < 0.01$) than the other seasons for all farm types (Table 2). In HRE and MRE farms, cotton receives the highest organic inputs, followed by maize, both of which are fertilizer-intensive crops. For LRE farms organic input priority was for cotton followed by millet and sorghum (Table 5).

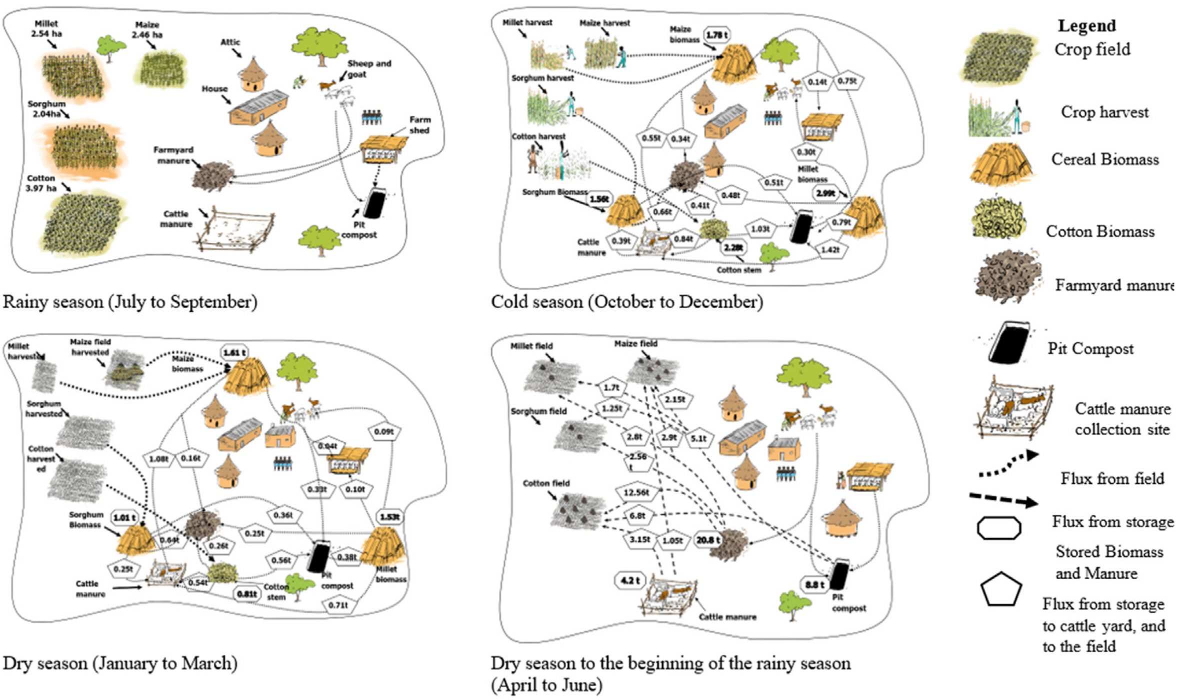
3.4. Nutrients from biomass and organic inputs and their allocation across farm typologies

3.4.1. NPK nutrients from biomass and organic matter

For biomass at field scale, the total NPK nutrients per hectare in HRE were 19.5 kg for N, 1.7 kg for P, and 41.3 kg for K, and these were 51% and 81% higher than the corresponding figures in MRE and LRE respectively (Supplementary V). The three organic input sources contributed similarly to the total nitrogen available as fertilizer in HRE. In MRE, it came mostly from compost and less from cattle manure and the total N available was lower than in HRE. LRE was significantly lower than HRE and the largest N value was from farmyard manure (Fig. 6). For phosphorus and potassium, the three organic input sources contributed differently to the three farm typologies and the highest amount came mainly from farmyard manure. Total phosphorus and potassium in HRE were significantly larger than in MRE and LRE, respectively (Fig. 6). At field scale the N, P, and K doses per hectare in HRE was significantly higher than in MRE and LRE. Nutrients application varied significantly for different crops and for farm typologies ($P < 0.001$). Cotton received the highest share of nutrients and HRE farms applied more fertilizer to cotton and maize than MRE and LRE farms (Table 5).

3.4.2. Nutrient partial balance per farm typology and per crop

The nutrient partial balance assessment conducted at the farm scale showed that for all farm typologies, the nitrogen balances were positive with an average of 20 kg ha^{-1} for HRE and MRE and 10 kg ha^{-1} for LRE. The phosphorus nutrient balances were nearly neutral for all farms, while potassium balances were negative, averaging -22 kg ha^{-1} for HRE and MRE farms and -10 kg ha^{-1} for LRE farms (Fig. 7a). Nutrient balances among the studied crops (cotton, maize, millet, and sorghum) indicated



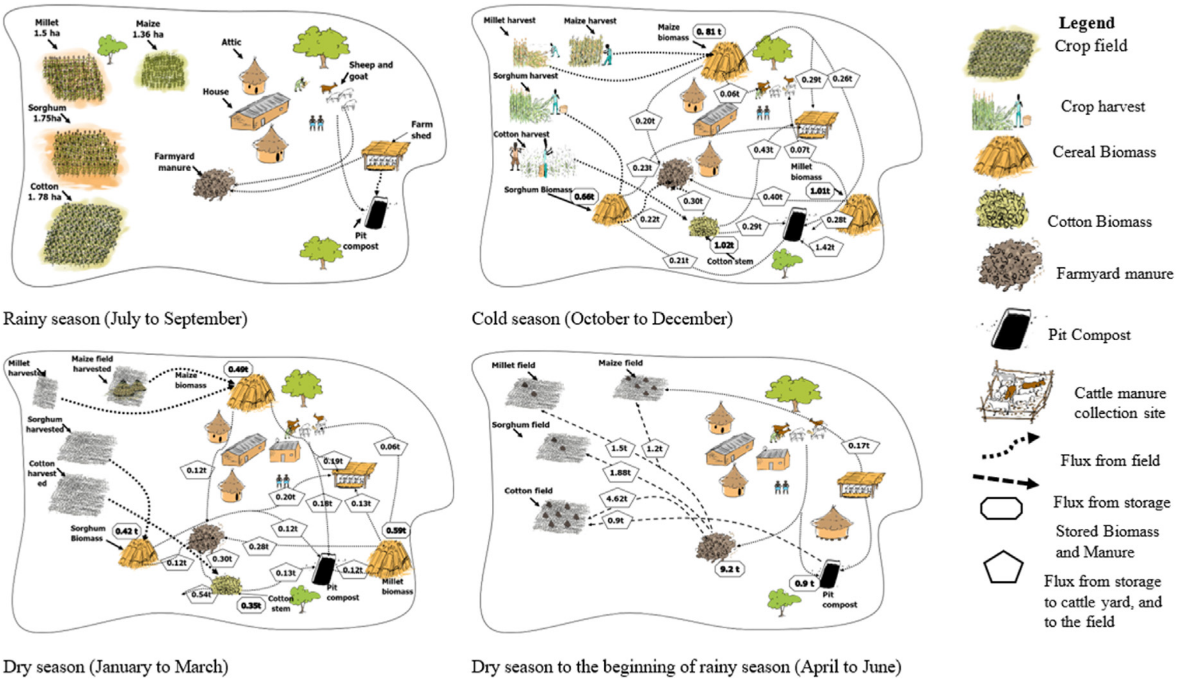
Rainy season (July to September)

Cold season (October to December)

Dry season (January to March)

Dry season to the beginning of the rainy season (April to June)

Fig. 4. Biomass and manure flows per period for MRE farms.



Rainy season (July to September)

Cold season (October to December)

Dry season (January to March)

Dry season to the beginning of rainy season (April to June)

Fig. 5. Biomass and manure flows per period for LRE farms.

significant differences ($P < 0.001$). For cotton fields, the nitrogen balance was positive at 40 kg ha^{-1} year^{-1}, a value twice that of the maize fields. In contrast millet and sorghum fields displayed nitrogen deficits (Fig. 7b). Cotton fields showed positive phosphorus balance whereas maize, millet, and sorghum fields, showed deficits, respectively. Potassium was critically deficient ($P < 0.001$) in all fields (Fig. 7b).

4. Discussion

The study showed that biomass and organic input production, transport, and stocks varied seasonally and is dependent on the level of farm endowment status (farm size, number of workers, livestock size, and available equipment). On average the HRE and MRE farmers produced 60 t and 34 t of biomass per year respectively, while approximately 10 t biomass was produced by LRE farmers per year. Similarly, the NPK amounts produced from HRE farms were 50% and 80% higher than those produced by MRE and LRE farms, respectively. The study's results confirm findings from previous studies which reported that farm-level endowment status determines the volume of biomass transported, stored, and used to produce organic inputs for soil fertility practices

Table 2
Quantity of Farmyard Manure, Compost, Cattle Manure per period and per farm types.

Year	Period	Farmyard manure (t) with HRE	Compost (t) with HRE	Cattle manure (t) with HRE	Farmyard manure (t) with MRE	Compost (t) with MRE	Cattle manure (t) with MRE	Farmyard manure (t) with LRE	Compost (t) with LRE	Cattle manure (t) with LRE
2019	Jul_Sept	10.9	4.16	3.18	8.9	2.33	2.04	4.03	0.36	0.021
	Oct_Dec	19.7	7.58	4.42	16.8	3.21	3.06	7.95	0.5	0.09
	Jan_Mar	39.1	11.4	11.6	19.0	8.78	3.39	7.03	0.75	0.17
	Apr_Jun	1.8	1.17	1.12	2.38	1.02	0.46	1.68	0.17	0.01
	Mean 2019	17.9	6.07	5.07	11.8	3.84	2.24	5.17	0.45	0.07
	F. Prob	<0.001	<0.001	0.002	<0.001	0.004	0.047	<0.001	0.66	0.60
	SED	5.14	1.18	2.65	2.33	2.2	1.12	0.99	0.47	0.13
2020	Jul_Sept	8.1	5.65	4.21	6.33	3.21	2.73	3.23	0.35	0
	Cct_Dec	15.9	10.6	5.66	14.5	5.49	4.13	7.66	0.42	0.17
	Jan_Mar	28.2	18.6	11.3	22.6	8.85	5.0	11.3	1.06	0.18
	Apr_Jun	2.5	0.82	2.29	2.05	0.49	1.7	1.37	0.08	0.17
	Mean 2020	13.7	8.9	5.86	11.37	4.51	3.39	5.9	0.48	0.13
	F. Prob	<0.001	<0.001	<0.001	<0.001	<0.001	0.017	<0.001	0.251	0.30
	SED	3.2	1.41	1.76	2.12	1.67	1.09	2.56	0.49	0.11
Mean Year		15.8	7.48	5.46	11.57	4.17	2.81	5.54	0.46	0.1
F. Prob. Year		0.18	0.02	0.54	0.80	0.53	0.05	0.40	0.89	0.34
SED		3.08	1.20	1.3	1.61	1.08	0.58	0.87	0.24	0.18

Table 3
Quantity of biomass per period and per farm type.

	Period	Biomass (t) with HRE	Biomass (t) with MRE	Biomass (t) with LRE
2019	Jul_Sept	0.49	0.35	0.16
	Oct_Dec	16.13	9.07	3.99
	Jan_Mar	6.34	3.45	1.31
	Apr_Jun	0.74	0.51	0.11
	Mean 2019	5.92	3.34	1.39
	F. Prob	<0.001	<0.001	<0.001
	SED	0.87	0.46	0.30
2020	Jul_Sept	0.26	0.19	0.01
	Oct_Dec	12.28	8.17	3.03
	Jan_Mar	9.94	6.46	2.4
	Apr_Jun	0.91	0.53	0.07
	Mean 2020	5.85	3.84	1.38
	F. Prob	<0.001	<0.001	<0.001
	SED	0.62	0.47	0.29
Mean Year		5.89	3.59	1.38
F. Prob. Year		0.95	0.43	0.96
SED		1.18	0.62	0.34

(Bonaudo et al. (2017) and Ismaïla et al. (2013)). Discussion on household to farm-level nutrient management and sustainability practices to de-risk environmental challenges are presented in sections 4.1 and 4.2.

4.1. Variations in nutrient management from biomass and manure

HRE and MRE farms produced more biomass than LRE farms. For example, the annual total biomass in HRE farms was 76% larger than LRE farms. Our finding corroborates with previously reported studies that highlighted LREs store low biomass quantities and abandon the remaining residue in the farms (Girard and Dugué, 2009; Blanchard, 2010; Vall et al., 2017). Our study indicated that upon deducting the portion allocated for composting, the remaining available biomass accounts for just 46% of the fodder requirements for livestock. These figures highlight the potential challenges in ensuring adequate feeding and sustenance for livestock owners, underscoring the importance of addressing the disparity by exploring alternative sources of fodder or biomass supplementation. Lack of feed results in the departure of animals to transhumant practices (Ayantunde et al., 2001, 2008) thus leading to a transfer of fertility (Andrieu et al., 2015) and intense pressure on natural resources (Brottem, 2016).

At the farm scale, nutrient management depends on farmers' decision regarding soil fertility management, which is also influenced by both socio-economic and biophysical environments, resource endowment and production objectives (i.e., land use and crop selection). Thus, more nutrient-based manure was applied to cotton and maize crops which results in a high monetary income. Distant farms from homesteads are considered remote, usually reserved for millet and sorghum, and receive low nutrient input (Table 5). In their report of farm variability in resource allocation, nutrient flows, and soil fertility status in Western Kenya, Tittonell et al. (2005) also reported that millet and sorghum crops are grown in distant locations from homesteads and utilize less nutrients. This has been a challenge for forage-based crop management practices (Ayantunde et al., 2014). Alternative options such as the perennial non-cultivated fodder, such as *Andropogon gayanus*, which can yield up to 22 t ha^{-1} biomass (ISRA/IRD/CIRAD, 2005) could be a potential opportunity for animal feeding and to increase manure production for LRE farm households.

Forage production from maize, sorghum (Sanon et al., 2007), and millet (Pasternak et al., 2012) must be scaled up for farmers to alleviate feed shortages. Similar to mineral fertilizers, assistance need to be

Table 4
Total Biomass (t), Farmyard and Cattle Manure (t), Compost (t) and Dosing (t/ha) values per farm typology.

Farm typology	Biomass (t)	Farmyard manure		Compost		Cattle manure		Total	
		Quantity (t)	Dose (t ha^{-1})	Quantity (t)	Dose (t ha^{-1})	Quantity (t)	Dose (t ha^{-1})	Quantity (t)	Dose (t ha^{-1})
HRE	22.3	33.5	1.69	14.1	0.71	11.5	0.58	59.1	2.98
MRE	13.4	20.7	1.81	8.8	0.76	4.2	0.36	33.9	2.94
LRE	5.35	9.2	1.44	0.9	0.14	0.17	0.03	10.3	1.61
Mean	13.7	21.2	1.64	8.23	0.54	5.26	0.32	34.4	2.51
F. Prob	< 0.001	< 0.001	>0.05	< 0.001	>0.05	< 0.001	>0.05	< 0.001	>0.05

HRE, high resource endowment; MRE, medium resource endowment; LRE, low resource endowment.

Table 5

Nutrient availability and application rates (doses in kg/ha) per farm typology and per crop.

Farm typology	Manure	Cotton			Maize			Millet			Sorghum		
		N	P	K	N	P	K	N	P	K	N	P	K
HRE	FYM	12.3	8.83	33.4	5.00	3.59	13.6	0.87	0.62	2.35	0.66	0.47	1.80
	Compost	10.5	1.71	8.23	13.5	2.21	10.6	4.58	0.75	3.60	3.90	0.64	3.06
	CM	15.1	2.06	13.0	9.01	1.23	7.8	–	–	–	–	–	–
	Dose (kg/ha)	12.6	4.20	18.2	9.18	2.34	10.7	2.72	0.69	2.98	2.28	0.56	2.43
MRE	FYM	9.3	6.67	25.2	3.45	2.48	9.4	3.37	2.43	9.17	3.62	2.61	9.85
	Compost	8.9	1.43	7.03	8.40	1.34	6.6	6.72	1.07	5.27	2.45	0.39	1.93
	CM	8.7	1.18	7.50	4.67	0.64	4.03	–	–	–	–	–	–
	Dose (kg/ha)	8.9	3.09	13.2	5.51	1.49	6.67	5.04	1.75	7.22	3.04	1.50	5.89
LRE	FYM	8.07	5.80	21.9	2.96	2.13	8.04	3.16	2.27	8.57	3.88	2.79	10.54
	Compost	10.3	1.44	8.09	–	–	–	–	–	–	–	–	–
	CM	–	–	–	1.43	0.23	1.28	–	–	–	–	–	–
	Dose (kg/ha)	9.17	3.62	14.99	2.20	1.18	4.66	3.16	2.27	8.57	3.88	2.79	10.54

HRE, High Resource Endowment; MRE, Medium Resource Endowment; LRE, Low Resource Endowment; FYM, Farmyard Manure; CM, Cattle Manure.

provided to farmers to facilitate access to forage seeds such as *Andropogon gayanus* (Kunth) and *Brachiaria ruziziensis.* Similarly, dual-purpose (food and feed) varieties of *Sorghum bicolor* such as Soubatimi and Tiendougou-coura, need to be facilitated. Promotion of fodder tree/shrub legumes such Leucaena leucocephala, Piliostigma reticulatum etc will alleviate feed shortages and address soil nutritional deficiencies (Birhanu et al., 2019).

The absence of, and limited access to, foundation seeds for forage seed multiplication, coupled with the consequent low economic profitability, pose significant barriers to the widespread adoption of forage production. In light of these challenges, maximizing the multi-functionality of associated crops becomes essential. Optimizing the combined benefits of crops for grain yield, forage production, and soil fertility enhancement, addresses challenges related to forage seed availability in addition to improving household economy and environmental management.

This approach diversifies agricultural activities and enhances resilience and sustainability within farming systems (Falconnier et al., 2023). In addition to their role in enriching soil fertility through atmospheric nitrogen fixation, Soybeans seeds (Glycine max L.) shows multifaceted utility within agricultural systems (Asodina et al., 2021). Among its diverse applications, women, in particular, employ the seed to produce the traditional food product “Soumbala” (Kabré et al., 2020). This transformation not only adds value to the seed but also serves as a significant source of income for those individuals (Asodina et al., 2021). Such integrated agricultural practices highlight the contributions of leguminous crops such as soybeans to de-risk environmental challenges and for improving socio-economic and agronomic significance in sustainable food systems (Ragsdale et al., 2022).

Regarding the distribution of manure per crop, we found that on HRE farms, cotton fields are fertilized with 5t farmyard manure per hectare, while maize fields receive only 3t farmyard manure per hectare corresponding to 65% of the fields in HRE and 47% in MRE. These findings can be attributed to farmers placing greater value on cotton and maize by supplying more organic inputs to these crops for economic purposes (Hussein et al., 2005). In addition, cotton is the main cash crop, and the production is bought by the Compagnie Malienne pour le Developpement des Textiles (CMDT), which provides farmers with credit facilities for fertilizer on cotton and maize (Falconnier et al., 2016). The income generated in this way can be used to support critical family needs, such as children's health and educational costs (Baquedano et al., 2010).

For millet and sorghum grown at MRE and LRE farms, the produced manure covers only 35% and 21% of the fields, respectively, versus barely 12% at HRE farms, in which these crops are primarily integrated into rotation practices to benefit from the residual fertilizer of cotton and maize fields (Tounkara, 2018). The reason millet and sorghum receive less manure or seldom receive any mineral fertilizer necessitates an increased application of mineral fertilizer or manure on millet and sorghum fields. Moreover, millet and sorghum yields are known to increase significantly when intercropped with a legume crop than grown as a sole crop (Trail et al., 2016). Improvement in the soil moisture and nutrient use efficiency for example through mulching that limits evapotranspiration (Sissoko et al., 2013) is the other recommended option for millet and sorghum fields. Integrating forage crops into agricultural production systems sometimes presents a complex dynamic, potentially endangering competition for water and soil nutrients. This interplay becomes particularly challenging when the associated crop assumes the form of an invasive legume species, such as cowpea (*Vigna unguiculata or Mucuna pruriens*). In such conditions, intercropping complicates the use of animal traction for weed management (Dugué et al., 2024). The delicate balance between maximizing forage production and mitigating resource competition underscores the need for nuanced management strategies to optimize agricultural productivity and sustainability in integrated cropping systems.

Furthermore, alongside seed subsidy policies, it is essential to explore opportunities regarding the implementation of a carbon payment system. Research indicates that when carbon is priced or monetized, the resulting benefit increase is comparable to, and sometimes even more significant than the benefits derived from a 50% subsidy (Marenya et al., 2012). This suggests that the carbon market offers a viable alternative for incentivizing the adoption of biomass management practices and soil fertility enhancement measures. If agricultural carbon initiatives are effectively implemented, they have the potential to enter markets with impact as for forestry projects (Kamyab et al., 2024). Therefore, harnessing the prospects of agricultural carbon through crop biomass management could present valuable opportunities for enhancing soil fertility and promoting sustainable agricultural practices.

4.2. *Sustainability practices to de-risk environmental challenges*

Early studies (van der Pol, 1992) on nutrient balances in sub-Saharan Africa indicated severe nutrient deficiencies in the farming systems, especially in the cotton zone of southern Mali, where 30% of farmers' income is from soil nutrients that have been mined and not replaced. Since the 1990s, possible solutions have been implemented through integrated crop and livestock systems (Ayantunde et al., 2019, 2020), including cattle corralling systems and systems in which crop residues are transformed into compost that is then mainly incinerated directly in the fields (Gandah et al., 2003). The pessimistic results of the 1990s have evolved into the relatively positive outputs (±3.2 kg N ha^{-1}) obtained around the 2000s (Kanté, 2001) supporting the findings of our study. Phosphorus has long been considered the primary limiting nutrient for cereal production in the Sahel (Bationo et al., 2015). However, our findings indicated that the phosphorus scenario has improved as a result

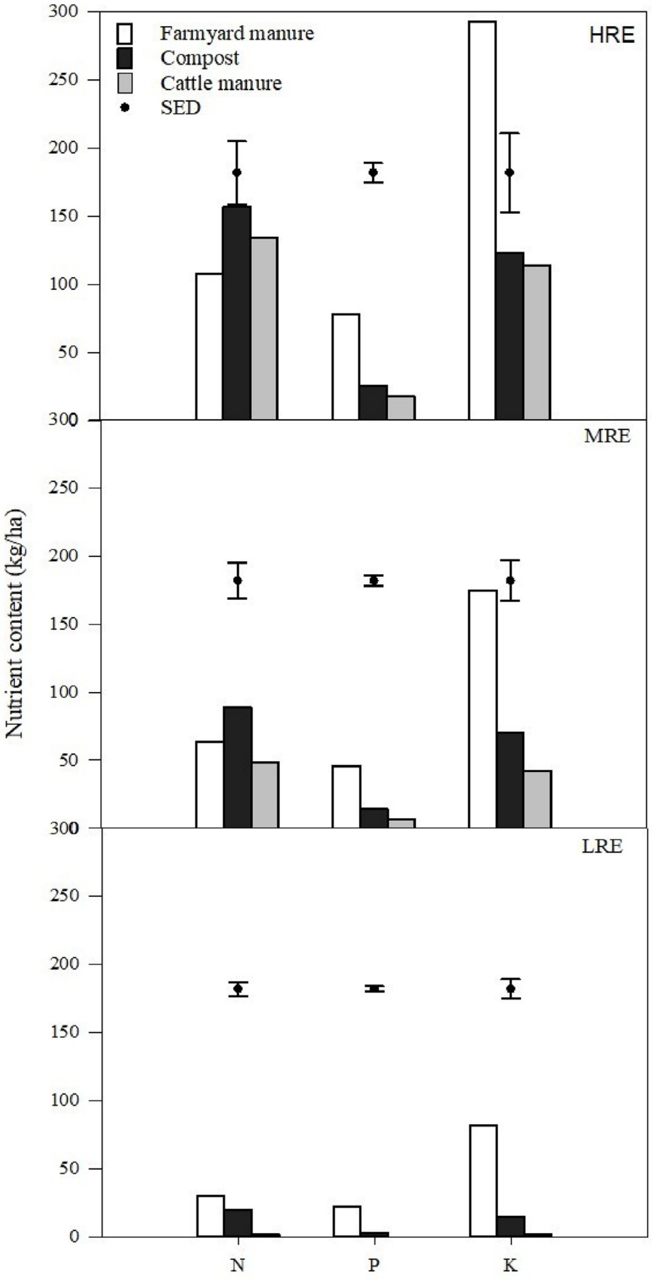


Fig. 6. Amount of nutrients (kg) based on type of organic inputs and organic sources in each farm typology.

of the continuous application of NPK fertilizer. This finding is also reported previously by Paul and Annicet (2018). The positive nutrient status might also be partially attributed to the advancements in small agricultural mechanization systems, which have improved the efficiency of the overall crop production system (Aune et al., 2017). Moreover, the popularization of rock phosphate application (Traore et al., 2007), which enhances the soil pH and leads to an increase in P nutrition, might have played a significant role in the mitigation of past P deficiencies (Bagayoko et al., 2000; Buerkert et al., 2000). The nutrient balances obtained herein reflect a positive nitrogen balance for cotton, which can be explained by the fact that cotton is the main cash crop and benefits up to 70% of farm-scale manure production in addition to mineral fertilizer inputs. At the same time, sorghum and millet receive little or no organic or mineral fertilizers (Gaborel et al., 2006). Thus, the residual effects of cotton fertilization are not sufficient to maintain nutrient balances under the current sorghum and millet cropping systems.

Although cotton-growing farmers receive input subsidies, mainly mineral fertilizer and seed, they need more financial means to purchase mineral fertilizers for cereal production. In this case, it is recommended that farmers adopt the micro-dosing approach (Ibrahim et al., 2016; Traoré et al., 2019). Micro-dosing technology has been developed and promoted by the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and its partners to help subsistence farmers in the drought prone regions to improve inorganic fertilizer application (Hayashi et al., 2008). For low resoruce endowed farmers in Zimbabwe for example, results consistently showed that micro-dosing technology can increase grain yields by 30–50% (Twomlow et al., 2008). In Nigeria, results of farm experimentation showed that millet farmers who practiced micro-dosing improved yields of millet and made more profit than those who did not (control) (Hayashi et al., 2008). In their study of rice intensificaion, Vandamme et al. (2018) highlighted that Phosphorous (P) micro-dosing can be an entry point towards rice based farming system in sub-Saharan Africa. This implies that micro-dose placement of nutrients in the planting hole can be used as an entry point towards sustainable intensification of the mixed crop livestock system in sub-Saharan drought prone regions. The micro-dosing approach practiced in the study area consists of hill placements of 6 g of NPK and 200 g of manure that corresponds to 60 kg ha^{-1} and 2 t ha^{-1}, respectively (Sogoba et al., 2020). This relatively inexpensive approach maximizes the residual effects of fertilization and improves the growth and production rates of millet and sorghum (Coulibaly et al., 2019; Ibrahim et al., 2015). This presents an opportunity for policymakers and extension workers to promote the micro-dosing technology under cereal cropping, especially in the regions where cotton is driving the fertilizer input system.

Potassium (K) deficiency was observed from the low-level organic inputs for sorghum and millet crops mainly for HRE farms resulting in poor grain quality (Gaborel et al., 2006; Hafsi et al., 2014). Whereas for LRE farms better application of farmyard manure (FYM) to sorghum and millet farms resulted in higher magnitude of K. Presence of few livestock in the study area enabled production of FYM and LRE farm households prioritized the organic input to the staple crops of sorghum and millet. Ayantunde et al. (2014) reported that in southern Mali, livestock rearing has become an additional activity especially for farm households with low endowment status. As the demand for livestock productivity and soil nutrient management increases overtime, less crop residues are left in most agricultural fields and hence accounting for the negative nutrient balance (Gerardeaux, 2009). The overall nutrient imbalance can be addressed through an integrated soil fertility management practices that includes revising mineral fertilizer application rates together with the use of improved organic inputs (Vanlauwe et al., 2014).

Gender dynamics play a significant role in agricultural practices and resource management. During the study period, our observation was that biomass and organic input flows, such as transportation and application, are predominantly carried out by the head of the households (usually men) and adult males in the household. Apart from this observation, our study was constrained by cost and time and did not include the study of social aspects. Further research is required to examine gender's role in biomass and organic input flows and implications for soil fertility improvement and the overall agricultural productivity in the region.

The study highlighted seasonal and annual biomass movement, nutrient flows, and stocks in the southern part of Mali that represent low agricultural input system and variation in household economic status. The methodology could be replicated in other regions with farm-level nutrient deficiencies and similarly affected by climate change. The study implies that endowment status in farm households determines nutrient flows and fertility levels of agricultural fields. Better-endowed farm households can improve soil health issues by replenishing essential nutrients through organic inputs.

5. Conclusions

In southern Mali, biomass stocks vary substantially among the

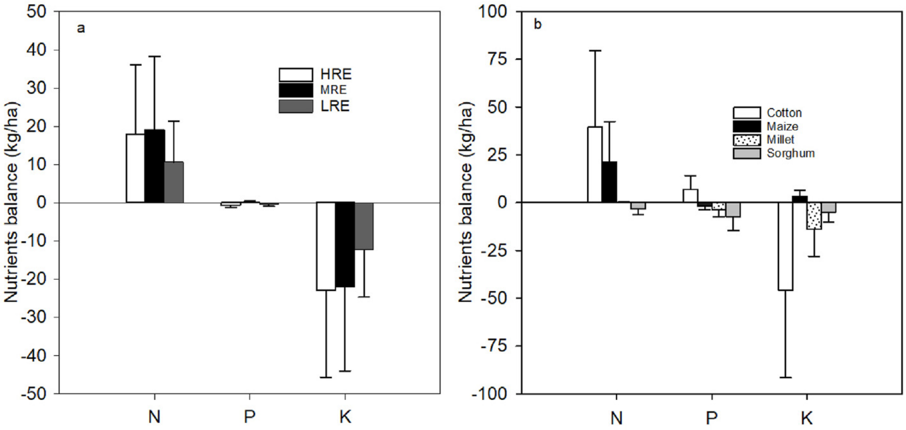


Fig. 7. Partial nutrient balance per farm types (a) and per crops (b).

different farm typologies. Significant differences in household labor and availability of farm resources contribute to the variation. The nature of cultivable land determines the choice of crops and biomass availability. In most cases, low resource-endowed (LRE) farm households use marginal lands, store low biomass quantities, and abandon part of the residues in the fields. Regarding organic inputs, high and medium-resource-endowed farm households provide more nutrient-based manure to cotton and maize crops, expecting high monetary income, unlike LRE, which prioritizes millet and sorghum to address household food self-sufficiency. Compared to the negative nutrient balances observed in the 1990s, the study showed that farm-level nutrient status has improved for the major crops grown in the study area. Cotton has a positive nitrogen balance, benefiting up to 70% of farm-scale manure production. The study implies that household endowment status determines farmlands' nutrient flows and fertility levels. Quantifying biomass transport and understanding nutrient flow dynamics enable the derivation of context-specific solutions to reduce risks associated with productivity and the environment.

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CRediT authorship contribution statement

Moumini Guindo: Writing – original draft, Formal analysis, Data curation, Conceptualization. **Bouba Traore:** Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **Birhanu Zemadim Birhanu:** Writing – review & editing, Validation, Supervision, Project administration, Methodology, Funding acquisition, Formal analysis, Data curation, Conceptualization.

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.farsys.2024.100109.

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