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# Determinants and Rationales of Crop-Livestock Integration in Sudano-Sahelian Mali

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Abstract The Sudano-Sahelian Mali once supported a ring system of land and soil management, with permanent croplands near housing compounds, a bush ring with fallow rotations, and an outer forest/savanna ring for grazing. Because of the expansion of permanently cropped fields into the bush ring, the landscape is now sharply dichotomised into the compound and forest/savanna rings. This ring management system features intensified internal recycling of nutrients from the forest/savanna ring to crop fields in the compound ring, supported by an integrated crop-livestock system. This study investigated how the villagers have maintained the crop-livestock integration against various resource constraints. We found that determinants and rationales of the crop cultivation and soil fertility management (SFM) practices commonly observed in Sudano-Sahelian West Africa have not changed. Those SFM practices (manure application from indigenous or improved pens and corralling) are the integration with diversified cattle grazing and transhumance patterns. The locations of watering sources and palatable pasture grasses and the SFM priorities of the cattle herd manager were the primary determinants and rationales of cattle management patterns in the study area. Increasing crop production will likely require exploiting untapped organic resources from peripheral forest/savanna rings and wider use of the improved pen and compost preparation techniques.

Keywords: Cattle grazing and transhumance patterns; Crop-livestock integration; Ring management system; Soil fertility management; Sudano-Sahelian Mali.

## Introduction

Sub-Saharan Africa (SSA) remains one of the last global regions struggling to attain food security (Mason-D'Croz et al. 2019). Current strategies rely on cereal imports, unsustainable nutrient mining, and area expansion, with consequent losses of biodiversity (Mueller et al. 2012; Pradhan et al. 2015; Sulser et al. 2015; OECD/FAO 2020). Even if the current on-farm yields on existing cropland in SSA were raised to the yield potential, they would be inadequate to meet future demand for cereals, which in 2050 is expected to be 335% of the 2010 level (van Ittersum et al. 2016). For Mali, demand is expected to rise to 365% of the 2010 level due to population growth, climate change, highly variable rainfall, low soil fertility, limited infrastructure, and political instability (van Ittersum et al. 2016).

The staple foods cultivated in the Sahelian zone (mean annual rainfall 250–500 mm; FAO 2004 using 1961 to 1990 data) and Sudano-Sahelian zone (annual rainfall 500–900 mm) in Mali are pearl millet (*Pennisetum glaucum*) and sorghum (*Sorghum bicolor*; Figure 1).

Yields of these crops are well below their potential, but inorganic fertiliser is rarely used in Mali except on cash crops like cotton or maize. Acid sandy soils in the West African Sahel have inherently poor fertility because they are very old and lack volcanic rejuvenation (Bationo et al. 2006). Crop fields in the Sudano-Sahelian Mali reportedly lost an average of 18 kg $ha^{-1}$ $y^{-1}$ nitrogen (N) (Powell & Coulibaly 1995). This is consistent with studies on soil nutrient balances conducted at a field scale across SSA, which generally all showed negative balances (Schlecht & Hiernaux 2004).

Earlier, the increase of crop production in the West African Sahel was characterised by extensification, i.e., expansion of cultivated areas (Aune & Bationo 2008). These indigenous farming systems have been based on shifting cultivation and long fallow periods to sustain soil fertility (bush-fallow system; Bationo et al. 1995). It co-existed with the pastoral system, where migratory pastoralists supplied manure to sedentary farmers in exchange for water, cereals, and crop residues (Williams et al. 1995). Since the 1970s, increasing human populations have caused an expansion of crop fields and reduced fallowing periods (Wezel & Haigis 2002), and the old soil fertility management (SFM) systems have gradually changed. The traditional bush-fallow system shifted towards permanent land cultivation in the West African Sahel. Because of the increased livestock population and reduction in grazing area, indigenous pastoralist systems have also been transformed (Powell et al. 1996). In the process, sedentary farmers became livestock owners, and migratory pastoralists settled and took up arable farming (Toulmin 1983).

Since the 1960s over the 1990s, the West African Sahel showed a dramatic decline in average precipitation (Mitchell 2005). With inherently low and declining soil fertility, external inputs, including inorganic fertiliser, was still marginal. With all these alarming pictures, researchers in the 1990s were concerned about the future food insecurity in the West African Sahel (e.g., Drechsel et al. 2001). However, the food security situation has improved. Cereal production in West Africa, Mali, Niger, and Burkina Faso covers 81%, 141%, 117%, and 107%, respectively, of the self-sufficiency needs for the five main cereals (maize, millet, rice, sorghum, and wheat) in 2010 (van Ittersum et al. 2016). It was not only the result of the expansion of the cultivated area but also of a detectable increase in yield per hectare (de Ridder et al. 2004). De Ridder et al. (2004) hypothesised that farmers counteracted the expected decline in soil fertility through the reallocation and intensified use of organic materials within their farming systems. These new SFM practices in the West African Sahel are characterised by an increasingly integrated crop-livestock system (Powell et al. 2004) and intensified internal recycling of nutrients (de Ridder et al. 2004).

Villages in the West African Sahel show a ring-like organisation (or a ring system of land and soil management) containing a compound ring, bush ring, and a forest or savanna ring (Prudencio 1993; Manlay et al. 2004a; Ramisch 2005). A compound ring closer to a residential area is devoted to continuous cultivation thanks to the manuring and spreading of household wastes. The bush ring is far from the residential area, and part of the crop fields in the bush ring is semi-permanent cultivation (fallow fields). A forest or savanna ring is the farthest from the residential area. Nutrient transfer from rangelands in the forest/savanna ring to crop fields in the compound ring (or internal recycling of nutrients) maintains the productivity of their crop fields and the sustainability of the Sahelian crop-livestock system (Powell et al. 1996). The nutrients lost from fields are returned to the fields mainly by manure application and/or corralling, i.e., parking herds in harvested fields, letting their dung and urine directly excrete onto the fields (Gandah et al. 2003). However, continuous population growth would lead to the disappearance of fallow fields (i.e., part of the bush ring) and the transformation of the ring-like organisation; hence, the need for intensified management of organic resources (Manlay et al. 2004b).

Aune & Bationo (2008) reviewed agricultural development in the drylands of West Africa Sahel (annual rainfall 400–800 mm). They showed the requirements for the innovative technologies introduced in agricultural intensification from millet- and sorghum-based low-productivity agriculture. First, using SFM techniques is the entry point for agricultural intensification because introducing other technologies, such as new crop varieties, have little impact if soil fertility in the field is not improved. Even an introduction of water-harvesting technologies alone does not show a sufficient yield increase (Zoumoré et al. 2003) or economic benefit (Fox et al. 2005) if the soil fertility problem in the field is not addressed. Thus, it would not give farmers much incentive to adopt the technologies. While the adoption rates of improved crop varieties had been similar in Asia, Latin America, the Middle East, and SSA during the late 1990s, such varieties contributed to 66–88% crop yield increases in the first three regions but only 28% in SSA. The potential of genetically improved crops cannot be realised when soils are depleted of plant nutrients (Bationo et al. 2012a). Thus, there is a need to invest more in SFM to strengthen farmers' motivation (Vanlauwe et al. 2010).

As a remedy against a long-term decline in soil fertility, a considerable number of improved crop production technologies, SFM practices, water-harvesting technologies, and others have been proposed to improve the productivity of African soils. However, farmers have adopted those proposed technologies minimally, or farmers have only partly implemented many of these (Schlecht et al. 2006; Mason et al. 2015). The low adoption by farmers can be ascribed to a combination of unfavourable factors, such as low-fertility soils, erratic rainfall, the occurrence of insect pests, and low prices for the produced commodities. These hamper subsistence-oriented farmers' investment (Breman et al. 2001) and make them take risk-averting strategies (Morduch 1995). Besides, the gaps between scientific findings and farmers' reality were pointed out to explain the low adoption rates (Mason et al. 2015). Most past research has not addressed the 'system' but one or two management practices (Mason et al. 2015).

Farmers' strategies for the reallocation and intensified manuring vary according to SFM practices used by individual farmers (Hayashi et al. 2006, 2012) and differ between farmers' groups, e.g., ethnic subgroups (Ramisch 1999, 2005), which reflect field-scale nutrient balances. Thus, researchers must investigate agro-pastoral farming and SFM practices used by individual farmers or groups to understand the integrated locally-specific crop-livestock system (Ramisch 1999). However, previous studies have discussed the part of crop and livestock separately, and its integration was rarely discussed in the local context.

The study area is the Sudano-Sahelian Ségou, Mali. This study aimed, first, to describe the local agro-pastoral farming practices. The main focus was the interrelationships between villagers' kinship groups, crop fields, SFM practices, and cattle grazing and transhumance patterns. Second, this study attempted to describe how villagers have coped with resource constraints, such as soil nutrient depletion and overgrazing of livestock, mainly caused by human and livestock population growth, maintaining the determinants and rationales of an integrated crop-livestock system. Finally, this study proposed intensified SFM practices using untapped organic resources in the Sudano-Sahelian Ségou, Mali.

## Materials and Methods

### I. Study area

The study area is Siakabougou village and its surrounding area in Boidiè Commune, Baraouéli Cercle, Ségou Région (Figure 1a). Siakabougou was selected as one of the project villages under a joint project (2008–2011) between Institut d'Economie Rurale (IER), Mali, and Japan International Research Center for Agricultural Sciences (JIRCAS).

Annual rainfall in Baraouéli town (the administrative centre of Baraouéli Cercle) is 682 ± 31 mm (Figure 2), falling in a single season from May to September (Agence Nationale de la Meteorologie, 1970–2006). The principal soils cultivated are yellowish sandy ferruginous tropical soils (in French soil classification; Drissa et al. 1999; Luvisols [plinthic, ferric] in FAO/UNESCO classification; Lucas & Chawel 1992). Grassland soils are gravelly ferrallitic soils (in French; Ferralsols [haplic, plinthic] in FAO/UNESCO). Siakabougou village territory covers 1,119 ha, and the largest area is forest (526 ha; 47% of the village area; Figure 1b), followed by cropland (294 ha; 26%) and grasslands (237 ha; 21%). The two forested areas (277 ha in the southeast and 249 ha in the southwest) were composed of savanna woodlands (trees and shrubs generally form a clear cover), tree savannas (trees and shrubs are scattered), shrub savannas (shrubs and fodder trees are scattered), and steppes (open grasslands). Between these two forest areas lie the main grazing areas (202 ha), which are open grazing steppes, grass savannas on shallow soils (*bowé*), and degraded bare land (*wala-wala*). The grasslands nearest the hamlets are referred to as *Fúga-ncini* (the 'small grazing area'; Table 1), while the remainder is referred to as *Fúga-ba* ('large grazing area'; Figure 1e). The Siakabougou villagers exclusively use *Fúga-ncini*. In contrast, people from surrounding areas (Kamba, Seribougou, Siankoro, Boidié villages and Baraouéli town; Figure 3) also use *Fúga-ba* for grazing cattle and collecting grass.

The human population of Siakabougou village was 325 in 2008 (29 people $km^{-1}$), while the livestock population was assessed at 250.2 TLU (tropical livestock unit)[(1)] or 22 TLU $km^{-1}$. The village contained two ethnic groups, the semi-sedentary Peulh and sedentary Sarakolé (or Soninke), living in distinct residential areas ('hamlets'; Figure 1b). The Peulh hamlet contained four extended families (known as *du* in Bambara, *concession* in French; Table 1), while the Sarakolé hamlet contained six. The *du* is an important kinship group for land tenure in Mali. Descendants of the same patrilineal ancestor share access to lineage resources (land, livestock, ploughs, and other draught equipment) according to their allocation by the chief of the *du* (the *dutigi*), who is usually the senior male (Becker 1990). While the *du* was the primary kinship grouping for Peulh and Sarakolé in Siakabougou, the smallest domestic units are known as *gă* (*manège* in French; hearth- or house-holds of people who eat together; Table 1). A *du* is composed of the plural *gă*; however, only the largest *du* in both hamlets (1 Peulh, 3 Sarakolé) contained multiple *gă*.

Under the joint project between IER and JIRCAS, a participatory ranking exercise using the priority grid (Paul 2013) was conducted. In the ranking exercise, the villagers rated the decline in soil fertility as the most severe problem in natural resource management. Labour is often the primary input in SSA, and its availability is critical for timing operations during the production cycle (Dahlin & Rusinamhodzi 2019). In the three villages of the joint project in Baraouéli Cercle, Ségou Région, including Siakabougou, no labour shortage issue was prioritised by the villagers.

## II. Field measurements, all-household survey, and semi-structured questionnaire surveys

Quick Bird satellite images in 2004 were used to create a digital topographic map of the study area. Quick Bird ortho-ready products were geometrically rectified using ASTER global digital elevation model ver. 2. For the 10 km × 15 km study area, 40 ground control points (GCPs), including centres of large trees, road cross-points, and corners of crop fields, were selected (Hughes et al. 2006). The XY coordinates of these GCPs were measured

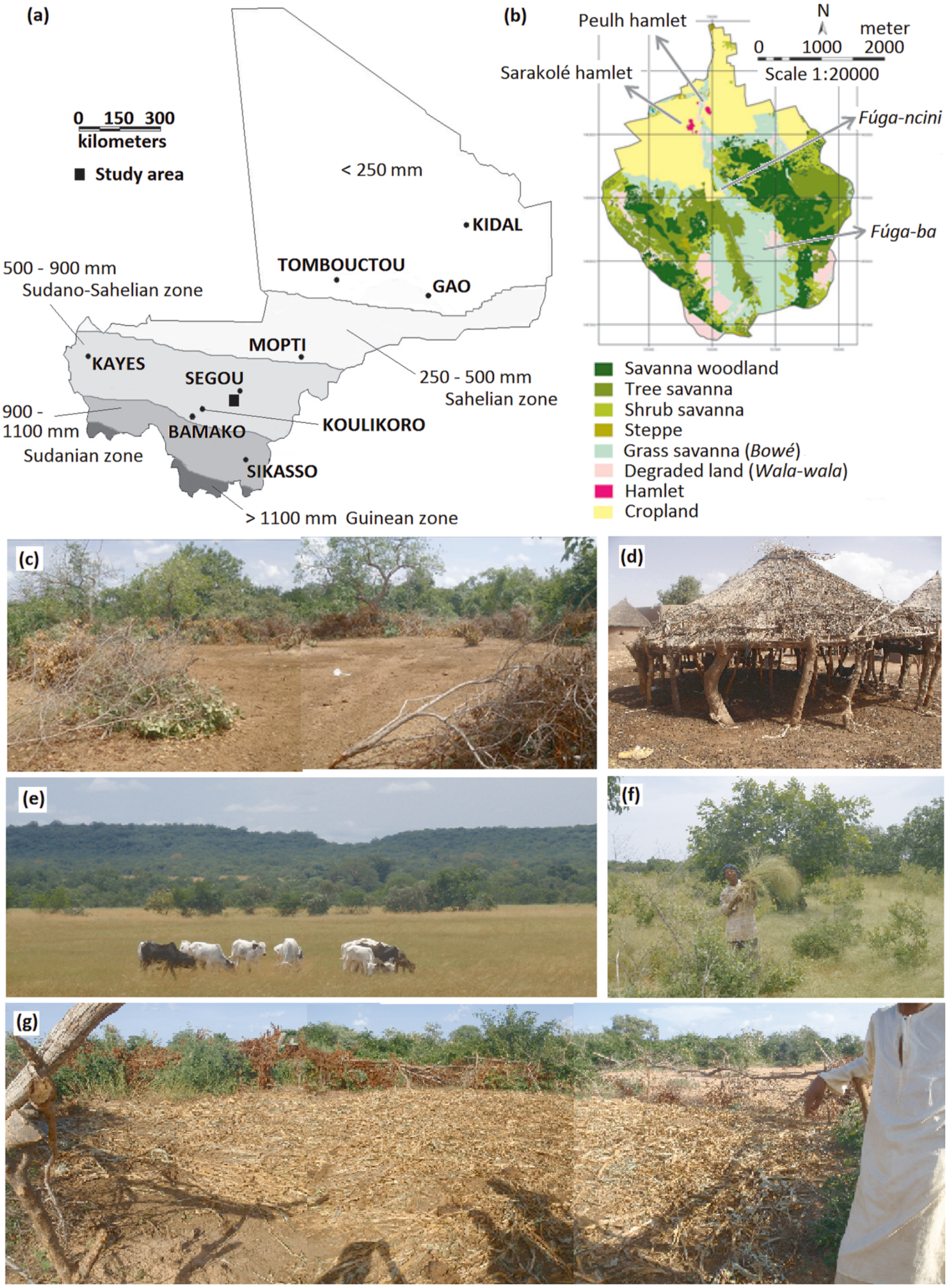


**Figure 1** a. Location of the study area (Siakabougou) in Mali with isohyetal lines. b. Major landscape features of the study area. c. A night pen set in *Fúga-ba*. d. A sheep and goal night kraal set in a hamlet compound. e. A cattle herd grazed in *Fúga-ba*. f. *Fúga-ba* with longgrass in mid-September. g. An improved pen set in *Fúga-ncini*.

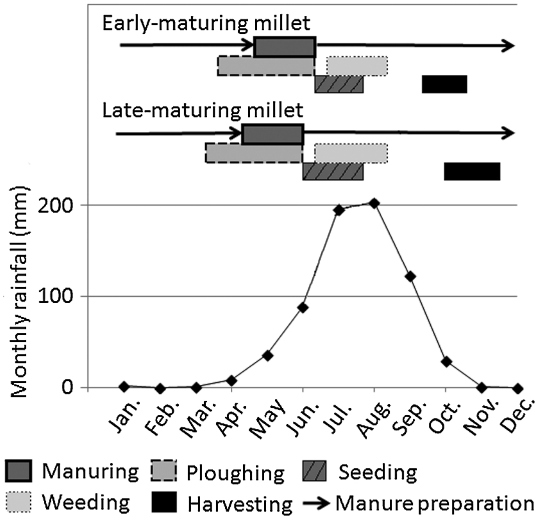


**Figure 2** Cropping calendar and monthly rainfall. Monthly mean rainfall data is from the Baraouéli rainfall gauge (1970–2006 with omission data during 4 years).

**Table 1** Local terms (all are in Bambara) used in this study

| Local terms | | Description |
|---|---|---|
| Kinship groups | *Du* | An extended family, which claims descents from the same patrilineal ancestor (*Concession*, in Malian French usage) |
| | *Gă* | Hearth- or house-hold, people who eat together (*Manége*, in Malian French usage) |
| Landscape | *Fúga-ba* | Large-scale complex of grass savannas (*bowé*) and bare land (*wala-wala* in Bambara) stretching into the central and southern parts of the Siakabougou territory |
| | *Fúga-ncíni* | Small-scale complex of grass savannas and bare land located near the Siakabougou hamlets |
| Crop fields | *Soforo* | Home fields or the ring of permanent fields located near hamlets in the original meaning (Gallais 1967). In this study, the home (*soforo*)-*du* field and home (*soforo*)-*gă* field are defined as permanent crop fields located near the hamlet (less than 300 m) and owned by the chief of *du* and collectively managed by the chiefs of *du* and *gă*, respectively |
| | *Kungoforo* | Bush fields in the original meaning (Gallais 1967). However, no fallow fields are observed in the vicinity of Siakabougou. Bush fields (*kungoforo*) can be defined as permanent crop fields located relatively far (more than 300 m) from the hamlet |

with an accurate Global Positioning System (GPS; Trimble GEO XT 2008 series). It has planimetric and altimetric accuracies at the sub-meter level. Based on these GCPs, second- or third-order polynomial transformations were performed to create new raster datasets using Arc GIS 10 (ESRI) with final root-mean-square errors (RMSEs) of 1.7 m (RMSEx) and 1.6 m (RMSEy). The XY coordinates data collected by the GPS in the fields were positioned on the digital topographic map using Arc GIS to calculate the area and draw digital maps. These GPS data were collected by walking with villagers along the boundaries of the village and their crop fields.

An all-household survey was conducted in 2008 together with a senior investigator of a consultant agent (Association pour la Gestion Integrée des Resources Naturelles: AGIRN). In the survey, all adult members were asked about their *du* (extended family) and *gă* (households), household composition, livestock ownership, and SFM practices. According to the field observation, farming systems and practices, including SFM, did not differ between Peulh and Sarakolé. The cropping sequence and quantity of manure applied to the field were ascertained from the largest *du* to observe the interaction between *du* and *gă*. The selected *du* (named Diallo) in the Peulh hamlet was composed of five *gă*. The data was collected from 2008 to 2010.

Field interviews and measurements (35 fields, 40.1 ha in total) and a laboratory soil chemical analysis were conducted to investigate Diallo *du* members' SFM practices. Villagers use donkey carts to carry cattle dung and/or manure (hereafter referred to as cattle manure) from the floors of night pens set in grasslands (Figure 1c) to crop fields. Manure refers to a decomposed organic fertiliser mainly made from cattle dung. Cattle manure made in an indigenous night pen is called *poudrette* in French (Blanchard et al. 2013).

Donkey and donkey carts are important animal draft power in Mali. A parastatal cotton company (the compagnie malienne pour le développement des textiles; CMDT) originally introduced the donkey cart in the late 1960s in southern Mali (Brock et al. 2002). Ramisch (2004) surveyed southern Mali in 1997 when about 10 years have passed since donkey carts were introduced in the surveyed area (Ramisch 2000). He found that 23% and 25% of sample households ($n$ = 44) owned donkey and donkey carts, respectively. In comparison, 66% and 57% of the households used donkey carts for carrying manure to the fields and harvested crops to their hamlets, respectively. The households borrowing a donkey cart used to 'pay' half of the transported manure to the cart owner's fields. Thus, villagers prioritised investing in equipment, especially donkey carts (Ramisch 2004). In 2007, 28 households in southern Mali surveyed by Blanchard et al. (2013) owned 1.2–3 donkey carts.

To estimate the quantity of cattle manure applied to each of the 35 Diallo *du* fields, the dry matter weight of manure loaded on a donkey cart was multiplied by villagers' recall of the number of cartloads transported to the field in 2008, 2009, and 2010. When asked about the number of cartloads carried to each field, we conducted group interviews with knowledgeable villagers on the site to supplement information. One donkey cartload of dried cattle manure was 271 kg, averaged across three sample measurements. This corresponded with the 250 kg measured for a full cartload of cattle manure as dry weight by the GERENA project (2008–2012) in Boidiè Commune, including Siakabougou (Tangara et al. 2012). The manure application rate to the field varied spatially and temporally. Limited studies conducted comparative experiments to investigate which scenario was more advantageous, an annual low-dose or high-dose application every other year (Kihanda et al. 2004). Grimes & Clark (1962), who conducted a study in the Coast Province, Kenya, concluded that an annual 3 Mg ha$^{-1}$ application and 9 Mg ha$^{-1}$ application once every three years had the same effects. Kihanda et al. (2004) suggested that the residual manure that plants did not use during the growth periods in the current season would be stabilised in soil organic matter. Therefore it does not matter whether manure is applied every season or in some seasons only. Considering these suggestions, an annual manure application rate was obtained by dividing the quantity of cattle manure applied to each field in a year by the area of the field. The average value over the three years was designated as the manure application rate of the field.

In keeping with practice throughout Mali (Gallais 1967; Ramisch 2005), villagers classified their crop fields into two types according to the distance from their hamlet, calling the fields less than about 300 m from the hamlet *soforo* (home fields; Table 1). Fields located farther than about 300 m are called *kungoforo* (bush fields). Soil samples were collected from the home (*soforo*) and bush (*kungoforo*) crop fields of Diallo *du* (eight randomly chosen locations, each from 0–20 cm deep). Analyses for organic carbon (C; modified Walkley-Black wet oxidation method; FAO 2019), total N (Kjeldahl digestion method; Bremner 1960), available phosphorus (P; Bray II; Bray & Kurtz 1945), and exchangeable bases ($Ca^{2+}$, $Mg^{2+}$, $K^{+}$, and $Na^{+}$) and cation exchangeable capacity (CEC) were measured at the Soil-water-plant Laboratory, IER (Bamako). Exchangeable bases and CEC were extracted with a 1 M acetate ammonium solution at pH 7 and determined by an atomic absorption spectrophotometer (FAO 2022).

Semi-structured interviews were conducted in 2010, targeting the owners and herders of cattle grazed in *Fúga-ba* grassland (Figure 1e). The 19 cattle herds belonged to *du* from 5 communities in Boidiè Commune (10 herds from Siakabougou, 5 from Siankoro, and 1 each from the villages of Seribougou, Kamba, and Djidabougou, and Boidié town; Figure 3). The ethnicities of the herd owners (*du* chiefs) were Sarakolé (9), Peulh (7), and 3 Bambara (another sedentary, Mandé-speaking ethnic group related to Sarakolé). Data collected included (i) annual cattle grazing and transhumance patterns, (ii) cattle ownership, and (iii) SFM practices. In 2010, the number of cattle grazed in *Fúga-ba* was counted. Based on it, the number of cattle owned by an owner was ascertained. Then the numbers for 2009 and 2000 (10 years earlier) were asked of the cattle herd owner and the herd boy. For less-structured interview questions asked in the semi-structured interviews, a

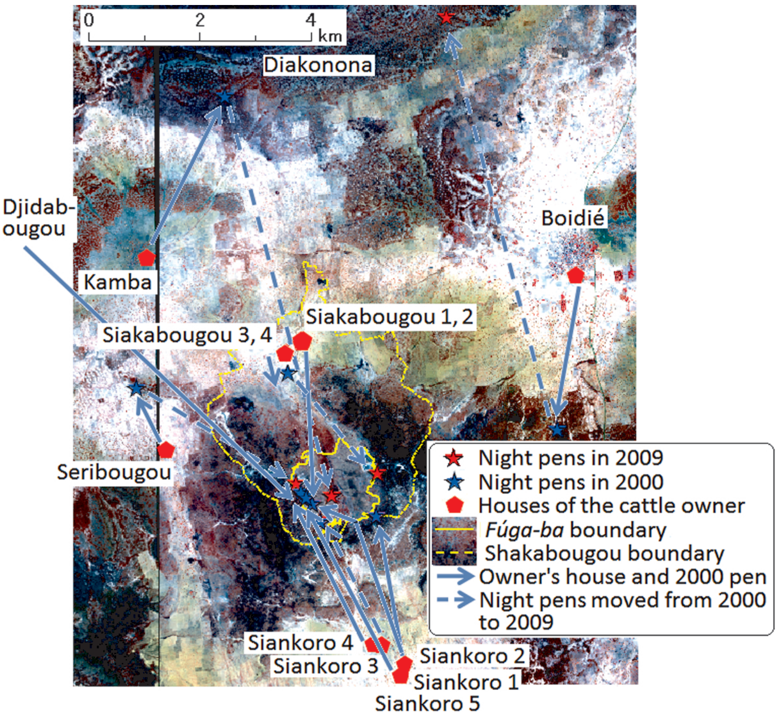


**Figure 3** Transition in night pen locations around *Fúga-ba*. The background is Quick Bird satellite images (bands 4, 3, 2 as RGB) taken in September 2009. A false colour treatment was made to turn vegetation in red colour. The thicker red colour indicates the denser vegetative biomass. White-looking places are generally crop fields, while red- or black-looking places are generally forests or grasslands.

narrative inquiry method (Clandinin & Huber 2002) was taken. The recorded interviews were transcribed into written English. Initial codes were created based on the emerging patterns most commonly seen in the transcribed texts (Cope 2003). To dig deeper into the processes, secondary codes were generated based on the frequency of appearances in the texts. Finally, emerging key themes were identified based on the secondary codes. SPSS ver. 20 (IBM) was used for the statistical analyses.

## Results and Discussion

### I. Kinship groups, land-holding, livestock ownership, and grazing patterns

As noted above, crop fields are managed either as collective fields of the entire *du* owned by the *du* chief or as household fields by each *gă* chief. Of the total crop field area owned by Peulh in Siakabougou, the *du* field and *gă* field areas each accounted for 50%, while those of Sarakolé were 64% and 36%, respectively (Table 2). In the Peulh hamlet, three of the four *du* only farmed *du*-fields (totalling 11.9 ha), while the largest *du* (Diallo) had collective *du* fields and private fields farmed by its five *gă*. The Diallo *du*-fields (14.0 ha) already exceeded the area farmed by the other three Peulh *du*, but with the inclusion of the 26.1 ha farmed as *gă*-fields, the Diallo *du* controlled 77% of the Peulh hamlet's crop fields. The Sarakolé hamlet had several large *du* that, like the Diallo *du* in the Peulh hamlet, comprised multiple *gă*, three of which also farmed both *du* and *gă* fields. The remaining three Sarakolé *du* had only *du* fields.

While Peulh is renowned in Mali as pastoralists, and the majority of cattle (218) in the village belonged to Peulh, there was no significant difference in the mean number of cattle owned by the Peulh *du* chiefs (55 ± 35; Table 2) compared with the Sarakolé *du* chiefs (10 ± 5). This suggests that regardless of ethnicity, the *du* chiefs generally saw the importance of livestock for the local farming system as a store of wealth, a means of redistributing nutrients, or a source of draft power. Within most *du*, cattle are managed as a collective resource. It is herded according to the wishes of the *du* chief (see below). The enumeration of the cattle herds grazed in *Fúga-ba* in 2000, 2009, and 2010 showed no significant

**Table 2** Summary statistics of kinship groups, land-holdings, and cattle ownership in Siakabougou

| Ethnic groups | Kinship group | | Crop field area (ha) | | | | | Cattle ownership and the number of head used for manuring crop fields | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | *Du* | *Gă* | Total area | Area (% of the total) | | *Du* field area per *du*[a,b] | *Gă* field area per *gă*[a] | Total head[c] | Head per *du*[a,b] | Head per a MU[d] | |
| | | | | *Du* field | *Gă* field | | | | | *Du* fields[a,b] | *Gă* fields |
| Peulh | 4 | 8 | 52.1 | 26.0 (50) | 26.1 (50) | 6.5 ± 2.5[ns] | 5.2 ± 0.7[ns] | 218.0 | 55 ± 35[ns] | 27 ± 10[ns] | 5 ± 3 |
| Sarakolé | 6 | 14 | 120 | 77.0 (64) | 43.0 (36) | 12.8 ± 2.1[ns] | 4.3 ± 1.2[ns] | 62.5 | 10 ± 5[ns] | 10 ± 5[ns] | 0 |
| Total | 10 | 22 | 172.1 | 103.0 | 69.1 | 10.3 ± 1.9 | 4.6 ± 0.9[ns] | 280.5 | 28 ± 15 | 20 ± 6 | 5 ± 3 |

[a] Mean ± standard deviation. *Ns* indicated that no significant different means ($p > 0.05$) were observed between Peulh and Sarakolé within the column (Mann-Whitney U test). [b] Each of the Mann-Whitney U tests reported an exact p-value corrected for ties (2-tailed) because the sample size of Peulh was less than 6 (Johnson 2009). [c] A calf was counted as 0.5 head. [d] MU, management unit of a cattle herd (*du* or *gă*). Cattle head per *du* allocated for manuring *du* fields (left) and cattle head per *gă* allocated for manuring *gă* fields (right).

differences in mean numbers (Mann-Whitney U test) between 7 Peulh (50 ± 17, 48 ± 19, and 45 ± 20 in the respective three periods) and 12 non-Peulh (39 ± 10, 27 ± 6, and 27 ± 6). While respondents felt that herd sizes had declined modestly since 2000, a one-way analysis of variance showed no significant difference in mean herd sizes between 2000, 2009, and 2010 for Peulh and non-Peulh.

Within extended families, the *du* chiefs allocate other livestock, such as sheep, goats, and donkeys, to the chiefs of constituent *gă*. Sheep and goats in Siakabougou were grazed mainly in *Fúga-ncini* over the year and parked at night kraals in the hamlets (Figure 1d). The modest amounts of manure from these kraals were transported to *gă* fields. In contrast, cattle manure is overwhelmingly applied to *du* fields: the head of cattle allocated to apply manure to the *du* field was an average of 27 ± 10 for Peulh and 10 ± 5 for Sarakolé (no significant difference; Table 2). None of the Sarakolé *gă* chiefs managed cattle on behalf of their *du* chiefs, and only the largest Peulh *du* (Diallo) entrusted his *gă* chiefs to manage his cattle herds. While they were expected to use these cattle to help manure the Diallo *du* fields, the five *gă* chiefs allocated an average of 5 ± 7 heads of cattle to manure their *gă* fields. All the cattle manure was applied to the fields before seeding the millet (Figure 2).

Given the importance of manure transport in Siakabougou, donkeys and donkey carts are key resources. Of 10 *du* in Siakabougou, only 2 Peulh *du* did not own either a donkey or a cart. Of the other 8 *du*, the chief of *du* owned 1.5 ± 1.2 donkeys and 1.3 ± 0.9 carts for the remaining 2 Peulh *du* and 1.8 ± 0.5 and 1.3 ± 0.3 for the 6 Sarakolé *du*. The 2 Peulh *du* who did not own either a donkey or a cart borrowed them from the remaining 2 Peulh *du* to carry manure to their *du* fields.

## II. Crop cultivation, manuring patterns, and manuring intensity

Combining the location designation, home (*soforo*) and bush (*kungoforo*) fields, and tenure designation, *du* and *gă* fields, crop fields in Siakabougou can be classified into four types: home-*du* field, bush-*du* field, home-*gă* field, and bush-*gă* field (Figure 4). The Diallo *du* chief owned 1 home-*du* field (3.7 ha) and 2 bush-*du* fields (10.3 ha in total; Table 3). The five *gă* chiefs of Diallo *du* cultivated 11 home-*gă* fields (2.7 ha in total) and 21 bush-*gă* fields (23.4 ha).

The mean *du* field area was 4.7 ha ($n = 3$), while the mean *gă* field area was 0.8 ha ($n = 32$).[(2)] The Mann-Whitney U test found that, when the farm size of only *gă* fields was compared, there was a significant difference in the mean-field area between the home (*soforo*) field (0.2 ha; $n = 11$) and bush (*kungoforo*) field (1.2 ha; $n = 21$) with $p < 0.01$. When 3 *du* fields (1 home-*du* and 2 bush-*du*) were added to the *gă* fields, there was a significant difference between the home field (0.5 ha; $n = 12$) and bush field (1.5 ha; $n = 23$); however, it was with $p < 0.1$. Thus, the farm size of the crop field in Siakabougou can have a negative gradient against the distance from the hamlet (Table 4).

Cropping sequences in these four field types in 2008, 2009, and 2010 were almost identical (Table 3). The most common crop was millet (occasionally intercropped with cowpea), planted in the home-*du*, bush-*du*, and home-*gă* fields and in most of the bush-*gă* fields (55 cropping times at 21 fields in the three years). Cowpea was intercropped with millet and sorghum only in the bush fields. Cowpea is useful for SFM and soil conservation (Dembélé et al. 2000). Not only does cowpea have N fixation effects, but it improves soil water infiltration. Stems and stover left are useful for soil amendment (Bationo & Ntare 2000). Because cowpea was harvested before millet and sorghum, it was less exposed to livestock damage. Early-maturing millet (harvested 75–90 days after planting) was recognised as emergency food for the hunger season (June to September;

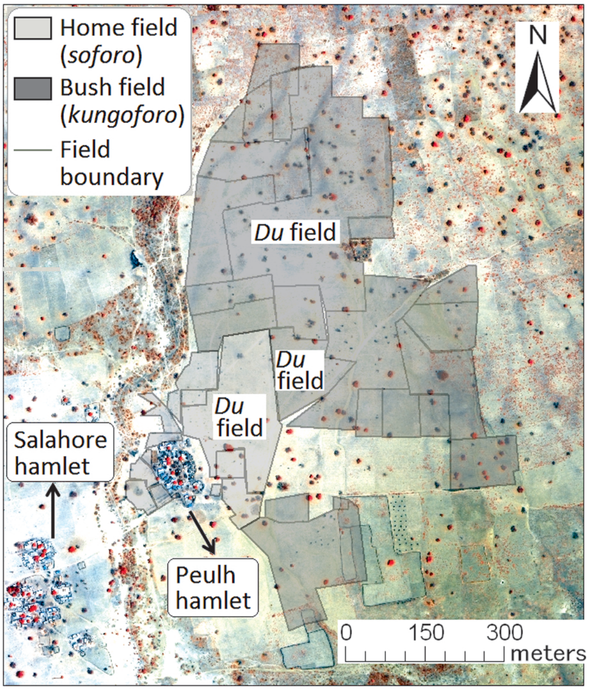


**Figure 4** Crop fields owned by the Diallo *du* chief. *Du* field indicates the home (*soforo*)-*du* or bush (*kungoforo*)-*du* fields, while other fields indicate the home (*soforo*)-*gă* or bush (*kungoforo*)-*gă* fields.

Figure 2). It was cultivated in home fields because it is vulnerable to bird attacks, and it was easier to keep watch from the hamlets. In bush fields, late-maturing millet (harvested 100–110 days after planting) was cultivated. Late-maturing millet produced higher biomass overall from the grain harvested as a staple food and from its stover and straw for animal feeds, construction materials, and fuel or left in the field as crop residues. Other crops were occasionally planted in the bush-*gă* fields, e.g., sorghum, watermelon or gourd, and groundnut. Groundnut, the only cash crop in the village, was cultivated on small bush-*du* fields separate from the main field block owned by Diallo *du*. It grows by exploiting residual fertility and improves soil fertility (Bationo & Ntare 2000). The difference in the growing period between early-maturing millet in home fields and late-maturing millet in bush fields allows households to spread their labour through the growing season. It also helps avoid labour bottlenecks, partly explaining why labour shortages were not identified as a critical constraint by the community (Table 4).

The Diallo *du* applied an annual average of 125.7 Mt of cattle manure to their fields from cattle herds' night pens in *Fúga-ncini*. While nearly two-thirds of this amount (86.4 Mt) was applied to their various bush fields, the largest single destination of transported manure was the Diallo home-*du* field (Table 3). The annual average of 120 cartloads (32.5 Mt) of cattle manure to the home-*du* field represented a massive logistical effort and sustained an application rate of 8.7 Mt $ha^{-1}$ $y^{-1}$. Respondents said that only when there was excess manure at the night pens (every two to four years) would they also transport it to the Diallo bush-*du* fields, which received only 1.1 Mt $ha^{-1}$ $y^{-1}$.

The *gă* chiefs of Diallo *du* were charged with ensuring the home-*du* field was properly manured; meanwhile, they also transported cattle manure to their *gă* fields. An annual

**Table 3** Cropping sequences taken in the crop fields of Diallo *du* and the intensity of cattle manure application in 2008, 2009, and 2010

| Types of crop field | | Cropping sequences | | | | | | Cattle manure application | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Crop fields (ha) | | | Cropping intensity[b] | Cropping sequences | | Manure applied | Annual application (Mt $y^{-1}$) | Annual application rate (Mt $ha^{-1}$ $y^{-1}$)[a] |
| | | No. plot | Total area | Area per field[a] | | | | | | |
| *Du* field | Home (*soforo*)–*du* | 1 | 3.7 | 3.7[cd] | 3 | | [large-particle, early-maturing millet] | Cattle | 32.5 | 8.7[ns] |
| | Bush (*kungoforo*)–*du* | 2 | 10.3 | 5.2 ± 3.4[c] | 6 | | [large-particle, late-maturing millet (+cowpea)] | | 6.9 | 1.1 ± 0.7 [ns] |
| *Gă* field | Home (*soforo*)–*gă* | 11 | 2.7 | 0.2 ± 0.1[d] | 33 | | [large-particle, early-maturing millet] | Cattle, sheep, goat, and donkey | 10.6 | 5.1 ± 0.9[ns] |
| | Bush (*kungoforo*)–*gă* | 21 | 23.4 | 1.2 ± 0.2[c] | 63 | 53 | [large-particle, late-maturing millet (+cowpea)] | | 75.8 | 4.4 ± 0.5 [ns] |
| | | | | | | 4 | [Sorghum]/[large-particle, late-maturing millet (+cowpea)] | | | |
| | | | | | | 3 | [watermelon or gourd] | | | |
| | | | | | | 1 | [large-particle, early-maturing millet] | | | |
| | | | | | | 1 | [small-particle, late-maturing millet (+cowpea)] | | | |
| | | | | | | 1 | [Sorghum] | | | |

[a] Mean ± standard deviation. The Kruskal-Wallis H test ($\alpha = 0.05$) was followed by the Dunn-Bonferroni test as a post hoc analysis. Different superscript letters within the column indicated a significant difference between the types of crop fields. *ns* indicated that no significant differences were observed between the types of crop fields. [b] Cropping intensity represented the total numbers of cropping in 2008, 2009, and 2010. For example, because the number of the home-du field was 1, cropping intensity = 1 field × 3 years = 3.

**Table 4** Determinants and rationales of the ring management system in two semi-arid West African Sahel

| Determinants and rationales | Sudano-Sahelian Mossi | | | Sudano-Sahelian Ségou | | Gradients[b] |
|---|---|---|---|---|---|---|
| | Inner ring | Intermediate ring | Outer ring | Home field | Bush fields | |
| Distance from compound | Near (25–55 m) | Intermediate (140–1,050 m) | Far (1,040–3,024 m) | Near (48–323 m) | Far (173–823 m) | + |
| Farm size | 0.03–0.30 ha | 0.06–0.78 ha | 0.89–1.05 ha | 0.5 ha ($n$ = 12) | 1.5 ha ($n$ = 22) | – |
| Main crops | Maize, tubers, sauce plants | Red sorghum, cowpea, groundnuts | Millet, white sorghum, cowpea, groundnuts | Early-maturing millet | Late-maturing millet, cowpea, groundnuts | |
| Function | Emergency foods | Staple foods, animal feeds, construction materials, fuel, crop residues | | Emergency foods | Staple foods, animal feeds, construction materials, fuel, crop residues | |
| Maturity period | 66 days | 137 days | 161 days | 75–90 days | 100–110 days | + |
| Livestock/bird damage | No damage | Bird attacks (sorghum, millet), livestock (cowpea) | | No damage | Bird attacks (millet), livestock (cowpea) | + |
| Management intensity | Intensive | Intermediate | Extensive | Intensive | Intermediate | – |
| 1) Soil fertility management | Manure and fertiliser application, N fixation by cowpea and groundnuts | | | Manure application, corralling, N fixation by cowpea and groundnuts | | |
| 2) Manure application rate[a] | 1.9–10.5 | 1.3–8.3 | 0 | 8.7 (*du*), 5.1 (*gă*) | 1.1 (*du*), 4.4 (*gă*) | –[c] |
| 3) Corralling period | No corralling practice(3) | | | About 2 months | About 1 month | – |
| 4) % of the area fertiliser used | 17–20 | 35–61 | 0–26 | No fertiliser applied | | – |
| 5) Fertiliser application rate[a] | 42–145 | 16–156 | 0–19 | No fertiliser applied | | – |
| 6) Intercropping | Maize + sauce plants | Sorghum + cowpea | Millet/sorghum + cowpea | No | Millet + cowpea | |

[a] Units are Mt $ha^{-1}$ $y^{-1}$. [b] Signs of the gradient against the distance from the compound commonly seen in both Sudano-Sahelian Mossi and Sudano-Sahelian Ségou. [c] No significant differences were observed between the home and bush fields.

average of 75.8 Mt $y^{-1}$ reached the bush-*gă* fields against 10.6 Mt $y^{-1}$ reaching the home-*gă* fields (Table 3). However, since the area covered by bush-*gă* fields was much larger, there was no significant difference in the mean annual application rates: 4.4 Mt $ha^{-1}$ $y^{-1}$ for the bush-*gă* and 5.1 Mt $ha^{-1}$ $y^{-1}$ for the home-*gă* fields.

The distance from the *Fúga-ncini* cattle night pens to the *du* fields was 3,218 ± 287 m ($n = 3$), while that of the *gă* fields was 3,125 ± 272 m ($n = 32$). The Mann-Whitney U test found that, when the distance from the *Fúga-ncini* pens to only *gă* fields was compared, there was a significant difference in the mean-distance between the home field (2,937 m; $n = 11$) and bush field (3,224 m; $n = 21$) with $p < 0.01$. When 3 *du* fields (1 home-*du* and 2 bush-*du*) were added to the *gă* fields, there was a significant difference between the home field (2,941 m; $n = 12$) and bush field (3,234 m; $n = 23$) with $p < 0.01$. Thus, the distance from the *Fúga-ncini* pens to the crop field in Siakabougou can have a positive gradient with the distance from the hamlet. Regression analyses applied to the distance from the *Fúga-ncini* pens to the crop field and the distance from the hamlet showed the linear models not to be statistically significant ($R^2 = 0.027$ and $p = 0.628$ for the home-*gă* field and $R^2 = 0.014$ and $p = 0.609$ for the bush-*gă* field; Figure 5a).

While the ring management hypothesis expects distance from the household compound to control nutrient inputs (Prudencio 1993), no significant difference was observed between the home fields (5.4 Mt $ha^{-1}$ $y^{-1}$ in the mean; $n = 12$) and the bush fields (4.1 Mt $ha^{-1}$ $y^{-1}$; $n = 23$) in the annual application rate.(4) This may be partly because, first, the source of cattle manure is the cattle night pens set in grasslands in the case of the Sudano-Sahelian Mali, not the household compound. Thus, the distribution pattern of cattle manure might be controlled by the distance from the position of the night pen. Second, all the Diallo *gă* were well equipped with donkeys and carts. The *du* fields (3.7 Mt $ha^{-1}$ $y^{-1}$ in the mean; $n = 3$) and the *gă* fields (4.7 Mt $ha^{-1}$ $y^{-1}$; $n = 32$) also showed no significant difference in the annual manure application rate. Thus, the cattle manure application pattern in the Diallo *du's* fields was little affected by distance or tenure types (except the one highly favoured home-*du* field; Table 3 and Figure 4).

The Kolmogorov-Smirnov test ($\alpha = 0.05$) and Shapiro-Wilk test ($\alpha = 0.05$) confirm that neither the home-*gă* field nor bush-*gă* field sizes were normally distributed. However, two variables (the field area and annual manure application rate) of both the home-*gă* and the bush-*gă* fields were log-normally distributed. Regression analyses applied to the two log-transferred variables showed the linear models to be statistically significant ($R^2 = 0.374$ and $p = 0.027$ for the home-*gă* field and $R^2 = 0.266$ and $p = 0.012$ for the bush-*gă* field; Figure 5b). Therefore, for both the home-*gă* and bush-*gă* fields, the *gă* chiefs of Diallo *du* tended to apply a higher intensity of manure to the field with a smaller area. Thus, the

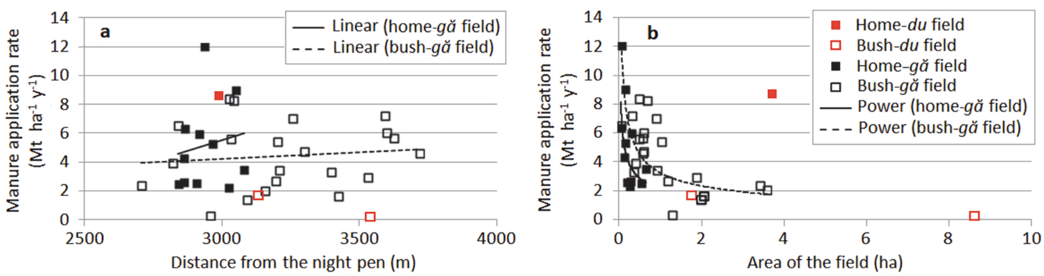


**Figure 5** Intensity of cattle manure application to the four types of fields (Diallo *du*) and the distance from the night pens (a) and the field area (b).

field area was the primary factor that significantly controls the intensity of cattle manure application to the *gă* field.

Beyond manure transport from animal pens, the Diallo *du* graze and corral their cattle herds directly on their bush-*du* and bush-*gă* fields after harvesting late-maturing millet to feed them on crop residues (Figures 2 and 6). While this corralling in the bush-*du* field (mid-November to mid-December) enables the direct incorporation of excretions in the soil beneath the pens, it also ensures cattle do not enter the hamlet compound and eat the crops as they are harvested and piled up. After threshing was over, the cattle pen for corralling was moved onto the home-*du* and home-*gă* fields (Figure 2). Around this period, cattle

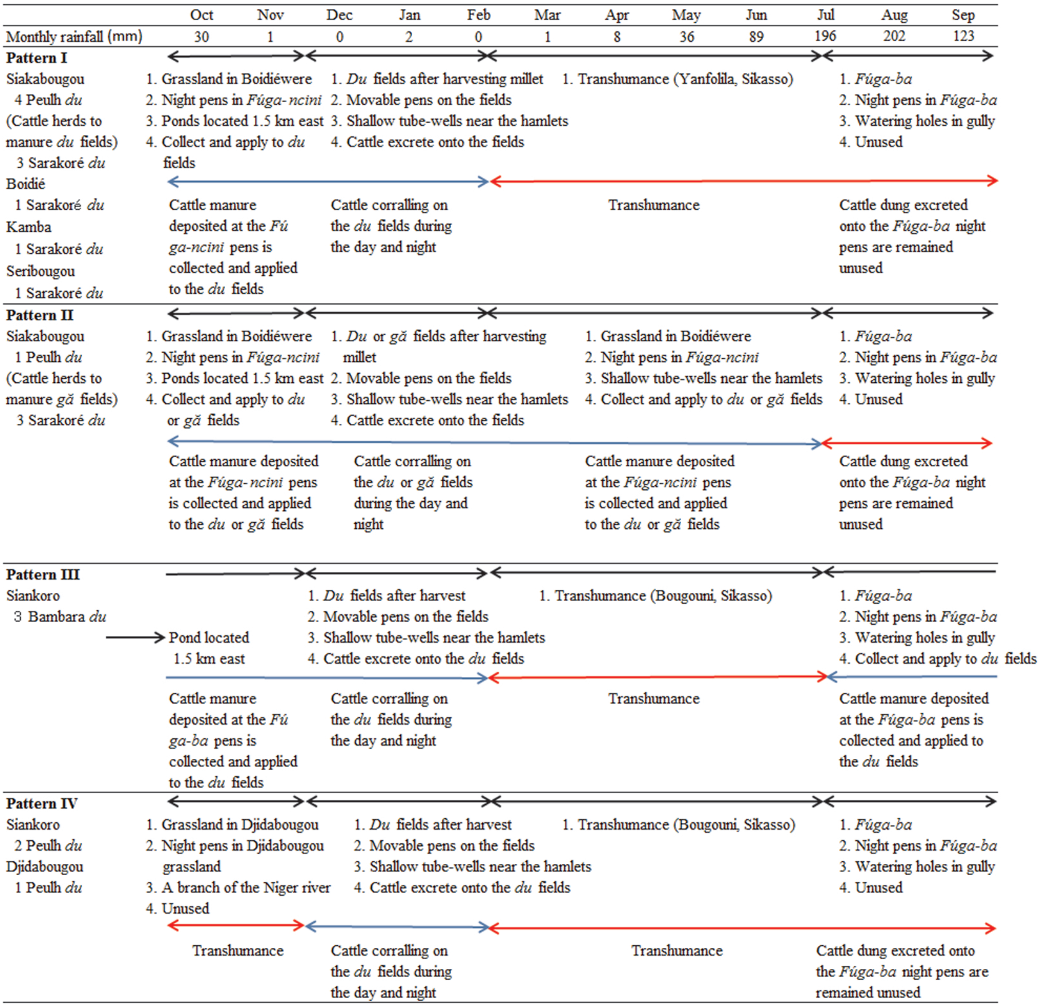


**Figure 6** Annual cattle grazing and transhumance patterns of the cattle herd managers (*du* chiefs). Four typically observed patterns were shown for the cattle herders who use *Fúga-ba* for grazing in the rainy season. Cattle grazing and transhumance in each period (1. Major feeds in the daytime, 2. Location of night pens, 3. Location of cattle watering holes, and 4. Uses of cattle excrement) were arranged in tandem. Blue arrows indicate when cattle excrement is used for soil fertility management. Red arrows indicate when cattle excrement is not used for soil fertility management. Monthly rainfall (mm) = the mean monthly rainfall in Baraouéli town.

**Table 5** Soil chemical and physical analyses in the home-*du* and bush-*du* fields of Diallo *du*[a]

| | Units | Home-*du* ($n$ = 8) | Bush-*du* ($n$ = 8) | Dembele et al. (2016; $n$ = 52) | Soil nutrient requirements[c] |
|---|---|---|---|---|---|
| pH | | 6.8 ± 0.2* | 6.2 ± 0.2* | 5.5 ± 0.3 | 5.0–6.5 |
| Total Organic Carbon (TOC) | % | 0.13 ± 0.07[ns] | 0.09 ± 0.05[ns] | 0.15 ± 0.14 | 0.2–1.2 |
| Total Nitrogen (TN) | % | 0.02 ± 0.01[ns] | 0.01 ± 0.01[ns] | 0.016 ± 0.007 | 0.04–0.15 |
| C:N ratio | | 7.9 ± 3.6[ns] | 8.0 ± 5.7[ns] | — | — |
| Available P | mg $kg^{-1}$ | 2.0 ± 0.3[ns] | 1.9 ± 0.3[ns] | 3.8 ± 1.1 | 6–22 |
| Cation Exchange Capacity (CEC) | cmol $kg^{-1}$ | 1.8 ± 1.0[ns] | 2.4 ± 0.8[ns] | — | 8–16 |
| Na | cmol $kg^{-1}$ | N.E. | N.E. | — | — |
| K | cmol $kg^{-1}$ | 0.01 ± 0.02[ns] | 0.01 ± 0.01[ns] | 0.02 ± 0.01 | — |
| Ca | cmol $kg^{-1}$ | 1.1 ± 0.7[ns] | 1.4 ± 0.5[ns] | — | — |
| Mg | cmol $kg^{-1}$ | N.E. | N.E. | — | — |
| % Sand[b] | % | 90 | 77 | 47–85 | — |
| % Silt[b] | % | 7 | 15.5 | 16–44 | — |
| % Clay[b] | % | 3 | 7.5 | 1–12 | — |

[a] Mean ± standard deviation. N.E. = negligible. The signs of * and *ns* indicate that significant and no significant differences (t-test; α = 0.05) were observed between the home-*du* field and bush-*du* field, respectively. [b] Bouyoucos hydrometer method. $n$ = 2 for each of the home-*du* and bush-*du* fields. [c] Oluwalosin (2005).

herds spent longer on the home fields (mid-December to mid-February) because these were closer to the village tube-well.

The sandy soils of the Sudano-Sahelian Mali are notoriously low in fertility (Powell & Coulibaly 1995). No significant differences in the soil nutrient levels between the home-*du* and bush-*du* fields were observed (t-test; α = 0.05) except for pH (Table 5). The home-*du* had a significantly higher pH (6.8), probably because cattle herds were parked longer at the home-*du* field, which received high-pH cattle urine. In West Africa, cattle urine pH is usually higher than cattle manure (Brouwer & Powell 1998; Schlecht et al. 2006). High pH positively affects millet yield (Diallo et al. 2019). Besides pH, higher manure application rates and longer duration of corralling for the home-*du* field generally positively influenced other chemical contents. However, these fields have much lower chemical contents than the standard millet crop requirements (Table 5). According to Oluwalosin (2005),[(5)] all the chemical properties of the millet fields rank not suitable for crop cultivation except for pH. Dembele et al. (2016) analysed some soil physical and chemical properties of the 52 soil samples collected from a 1,157-ha area (mainly including grasslands and crop fields; about 32 km south of Siakabougou) in the Sudano-Sahelian Mali (Table 5). Low soil chemical properties of the crop fields in Siakabougou appear to represent those of the Sudano-Sahelian Ségou. Thus, the villagers' efforts to transport manure and the strategic corralling of herds in the dry season appear to help maintain a minimal level of soil nutrients in the Diallo fields (Table 5).

III. Determinants and rationales of cattle grazing and transhumance patterns

The semi-structured interviews conducted with the 19 *du* chiefs found four main cattle grazing and transhumance patterns (Figure 6), managed by (i) pattern I: 10 *du* containing 4 Peulh (Siakabougou) and 3 Sarakolé *du* (Siakabougou, Boidié, Kamba, and Seribougou),

(ii) pattern II: 4 *du* containing 1 Peulh (Diallo *du*, Siakabougou) and 3 Sarakolé *du* (Siakabougou), (iii) pattern III: 3 Bambara *du* in Siankoro, and (iv) pattern IV: 3 Peulh *du* (2 Siankoro and 1 Djidabougou). All of the interviewed 19 *du* chiefs noted that they had difficulty finding suitable cattle grazing sites with a watering hole and palatable pasture grass after the rainy season every year, which accounted for the emergence of distinct, annual grazing strategies as solutions. Common to all four patterns were the practices of (i) in the rainy season, from mid-July to late September, grazing cattle herds in *Fúga-ba* in the daytime and parking them at *Fúga-ba* night pens (Figures 1c and 3). Plus (ii) from mid-November to mid-February, parking cattle herds on their bush-*du* or bush-*gă* fields after late-maturing millet has been harvested, i.e., corralling. Differences were found in two periods: mid-September to mid-November and mid-February to mid-July.

Pattern I: Siakabougou villagers move night pens from *Fúga-ba* to *Fúga-ncini*, closer to their hamlets, during mid-September (Figure 6). At that time, they also move the daytime grazing area from *Fúga-ba* to a grass savanna in Boidiéwere, a neighbouring village. This is because, first, they lose suitable drinking water sources around *Fúga-ba* after mid-September. *Fúga-ba* does not have any large watering holes or well. In the rainy season, cattle drink water from gullies and shallow depressions; however, these watering holes are dried up later. Second, after mid-September, the biomass of short grasses cattle prefer to eat becomes lower in *Fúga-ba*. Cattle prefer dominant long grasses in *Fúga-ba*, such as *n'gassan* (Bambara; *Loudetia togoensis*) and *yayalen* (Bambara; *Andropogon pseudapricus*), only in the early rainy season (June and July) when green grasses sprout. After mid-September, when these long grasses reach flowering and reproduction stages, cattle avoid eating them (PROTA4U web database 2017a, 2017b).(6) After that, as rainfall reduces, *Fúga-ba* falls into an overgrazed condition where the cattle have eaten up palatable short grasses. A similar pattern of cattle eating only a fraction of herbaceous biomass with a rich feed value has also been observed in other Sudano-Sahelian West Africa, e.g., northern Burkina Faso (Quilfen & Milleville 1981). In southern Senegal (annual rainfall 960 mm), only 29% of available herbaceous forage on the village territory was eaten by village animals (Manley et al. 2004b).

All the cattle herds were parked in the *Fúga-ba* night pens in the rainy season; however, all the *du* chiefs left the cattle dung in the pens unused. They explained that the quantity of dung left was insufficient and the quality was not good. On September 28, 2010, we measured the quantity of dung left in two *Fúga-ba* pens owned by the chiefs of Diallo *du* and Traoré *du* (both were Siakabougou). Air-dry weight of 617 kg from the Diallo *du* pen and 421 kg from the Traoré *du* pen were collected. In 2008, 2009, and 2010, a mean of 116 cattle heads per year was allocated by the chief of Diallo *du* to manure their *du* fields. Those herds were parked in the *Fúga-ncini* night pens from mid-September to mid-November and provided the mean 39.4 Mt $y^{-1}$ of manure. The manure production rate was 5.7 kg $head^{-1}$ $day^{-1}$. In contrast, cattle herds parked at the two *Fúga-ba* pens for about 2.5 months produced manure at only 0.1 kg $head^{-1}$ $day^{-1}$ for both pens. The amount of dung left in the two *Fúga-ba* pens per animal was dramatically lower. It was because (i) the herds spent much more time grazing extensive areas away from the night pens and (ii) no measures were taken to keep rainfall and runoff from washing dung away. Besides its quantity, much of the dung left in the two *Fúga-ba* pens was crumbled and mixed with sand. This poor organic quality of manure is a feature of traditional manure, *poudrette* (Ganry et al. 2001).

Until mid-November, Siakabougou villagers park their cattle herds in the *Fúga-ncini* night pen. Around this time, the ponds that have held water since mid-September dry up. They shift daytime grazing sites to their bush-*du* fields, where they have harvested late-maturing millet (Figures 2 and 6). They also change the source of drinking water to the shallow tube-well set near their hamlets. From mid-February to mid-July, patterns I, III, and IV take out all their cattle, except oxen, to Sikasso Région, the southern-most region of Mali (the Sudanian zone, annual rainfall 900–1,100 mm, or Guinean zone >1,100 mm) for transhumance mainly because of a shortage of palatable pasture grass.

Pattern II: Three Sarakolé *du* and all *gă* chefs in Diallo *du* (both are Siakabougou) do not send their cattle herds on transhumance from mid-February to mid-July. Instead, they graze the herds in *Fúga-ncini* in the daytime and park them at *Fúga-ncini* night pens (Figure 6). Cattle drink tap water from tube-wells. In this season, because the quantity of palatable grass is limited, villagers sometimes provide cattle herds with crop residue and stover in an improved pen (i.e., one with added bedding; Blanchard et al. 2013; Figure 1g). Dung deposited on the pen floor is collected and applied to *du* or *gă* fields. The Mann-Whitney U test showed significant different means in the cattle heads managed by *du* or *gă* chiefs between pattern II ($n$ = 7) and other patterns (I, III, and IV; $n$ = 20; $p < 0.05$). A cattle herd manager who selects a combination of grazing local grass and feeding crop residue from mid-February to mid-July has a smaller cattle herd (11 ± 12 heads), probably because of the limited feed source in the harshest period on the village territory. All the 10 *du* chiefs in Siakabougou owned oxen. Of them, all oxen owned by 3 Sarakolé *du* and 1 Peulh *du* (Diallo *du*) took pattern II. The other six Siakabougou *du* kept their oxen tethered near the hamlets through the land preparation period. Those *du* that took patterns I and II commonly moved their daytime grazing area, watering sources, and night pens from *Fúga-ba* to somewhere closer to their hamlets by mid-September. If they had lacked those resource endowments, they would have been forced to seek other alternatives like patterns III and IV.

Pattern III: Three Bambara *du* in Siankoro kept their cattle herds in *Fúga-ba* even after the other cattle herds had left there around mid-September (Figure 6). They kept the herds in *Fúga-ba* until late November by supplying drinking water from a large pond near their hamlet and grazing short grasses left in *Fúga-ba*. They did so partly because they expected a larger quantity of manure would be left in their night pens by keeping their cattle herd in *Fúga-ba* for longer.

Pattern IV: Two Peulh *du* in Siankoro sent their cattle to Djidabougou (a village in Boidiè Commune) to seek drinking water and palatable pasture grass (Figure 6). These two Peulh *du* had taken pattern I until 2007; however, they found it difficult to locate a suitable grazing area around Siankoro from mid-September and decided to send their cattle herds to grassland in Djidabougou where a branch of the Niger river is located. They said that their *du* fields were narrow and were sufficient to maintain the soil fertility by cattle corralling from mid-November and manuring sheep and goat dung.

Thus, three major factors determined cattle grazing and transhumance patterns; (i) location of stable watering sources, (ii) quality and quantity of pasture grasses, and (iii) possible uses of cattle excrement for SFM. Of these factors, (i) and (ii) vary widely in time and space, particularly from September to February, and 5 of the 19 cattle herd owners changed their grazing and watering locations between 2000 and 2009 (Figure 3).

## IV. Determinants and rationales of cropping systems in the drylands of the Sahel

In Sudano-Sahelian Mali, including Boidiè Commune, a compound ring and forest/savanna ring were observed, whereas no bush ring was observed. Almost all crop fields were under continuous millet-based cropping. Fallow fields in Boidiè Commune disappeared from the 1950s to the 1980s, according to the interviews in the three villages of the joint project (Caldwell 2009; see also Dembélé et al. 2000).

In the Sudano-Sahelian Mossi cropping system in Burkina Faso, the ring management system for land and soil was typically seen. Prudencio (1993) found the management and land-use intensity of crop fields highest in the inner rings (compound ring), declining towards the outer ring (bush ring).(7) He also found that (1) the distance from the household compound to the field, (2) the maturity period of crops and varieties, (3) the probability of livestock damage to crops, and (4) the natural fertility base of soils were the determinants and rationales of the farmers' soil and crop management strategies to alleviate (i) soil moisture, (ii) soil fertility, and (iii) labour constraints (Table 4). In the Mossi cropping system, maize, tubers (sweet potatoes and yam; emergency foods for the hunger season), and sauce plants (okra and sorrel; complements to daily diet) are intercropped. Maize is often harvested before maturity (60–90 days)(8) and often eaten raw to weather a food shortage in the hunger season (June to September). Second, it is to avoid bird attacks, a major problem for early maturing food crops in the region. The crops cultivated in the inner ring require intensive management with more labour for seedbed preparation, manure application, and weeding. However, the farm size in the outer ring was the largest (0.89–1.05 ha; *n* = 109), followed by the intermediate ring (0.06–0.78 ha; *n* = 120), and that in the inner ring was the smallest (0.03–0.30 ha; *n* = 96). Because the outer ring fields are wider and farther than the inner and intermediate fields and late-maturing crops are bulky, it is usually harder to work in the outer fields. Maize (inner ring), red sorghum (intermediate ring), and millet and white sorghum (outer ring) have longer mean maturity periods in this order; 66, 137, and 161 days, respectively. Farming practices, such as planting, weeding, and harvesting, are performed from the inner, intermediate, and outer rings. The differences in crop maturity periods help alleviate labour bottlenecks.

Cowpea is cultivated in the outer ring, intercropped with cereals because it is easily damaged by livestock and is useful for SFM and soil conservation. Cowpea does not grow well in fields with intensive manuring. Groundnut, a cash crop, is grown in small plots across the intermediate and outer rings to exploit residual fertility and improve soil fertility (Prudencio 1993).

The most commonly identified relationship in the agricultural landscape is the gradient of decreasing nutrient inputs with increasing distance from the household compound or livestock pen (Prudencio 1993; Manlay et al. 2004a; Ramisch 2005). However, in southern Mali (the Sudanian or Guinean zones, annual rainfall >900 mm; Figure 1a), where farmers preferentially apply organic and inorganic fertilisers to cotton and maize, there was no relationship between the locations of these two crops and the distance from the compound (Ramisch 2005). Households with scarce resources were likely to concentrate organic and inorganic fertilisers for the hotspot fields with their favourable crops for maximum benefit. In contrast, households with access to more of those resources would either increase the number or the area of those hotspot fields, thereby reducing the overall patchiness of their input use (Ramisch 2005). In the Sudano-Sahelian Mossi cropping system, farmers supplied farmyard manure more on the two cropping sequences: one was maize intercropped with sauce plants and sometimes tubers cultivated in the inner ring, and another was red or white sorghum and millet cultivated in rotation cultivated over the intermediate to outer rings. Maize and tuber as emergency crops and sorghum and millet as staple food crops were important for the villagers. The mean 8 $Mg\ ha^{-1}\ y^{-1}$ of manure and sometimes inorganic fertilisers were applied to the former cropping sequence. The mean 2 $Mg\ ha^{-1}\ y^{-1}$ of manure was applied to the latter one (Prudencio 1993), probably using donkey carts owned by themselves (Matlon 1980) or by renting (Batterbury 1996).(9)

In southern Senegal, millet fields received the highest animal excrement (57% of the estimated total weight). Besides it, whether the crop fields were in the compound ring or bush ring, the most intensively manured fields (night corralling) were mixed stands of maize and millet > maize alone > millet alone > sorghum alone in this order (Manley et al. 2004b). Siakabougou villagers value early-maturing and late-maturing millet as an emergency crop and staple food, respectively. Diallo *du* took the diverse SFM practices to concentrate and redistribute their scarce resources to favourable crop fields for maximum benefit, consistent with those in other Sudano-Sahelian West Africa.

Although the prevailing crops and SFM practised differing between the two cropping systems, the determinants and rationales of the ring management system observed in the study area match those in the Mossi cropping systems and other parts of the Sudano-Sahelian West Africa (Bationo et al. 2012b; Table 4). These determinants and rationales of the cropping sequences and SFM strategies continue to operate even after the ring-like organisation has been transformed due to continuous population growth. In the absence of external inputs, increasing crop-livestock integration represents the common response to meet the growing need for intensifying low-productivity millet and sorghum-based agriculture (Manlay et al. 2004b; Aune & Bationo 2008). The intensified SFM practices tap presently unused organic resources from the peripheral forest/savanna ring (e.g., uneaten herbaceous forage by animals on the village territory) to effectively use it to support rainfed food crops in the compound ring.

## V. Candidates for intensified cattle manure preparation methods in the Sudano-Sahelian Mali

In southern Mali, the parastatal cotton company (CMDT) promoted agricultural packages, including credit for seed, inputs (inorganic fertilisers, herbicides, and pesticides), and animal traction (ox-drawn ploughs and donkey carts; Landais & Lhoste 1993) since the late 1960s. Some intensified cattle manure preparation methods now locally observed in southern Mali are an integration of farmers' indigenous knowledge and introduced knowledge by CMDT (Brock et al. 2002). The introduced SFM techniques include a combination of improved pens (Figure 1g) and different types of compost preparation techniques (Bodnár 2005). Local cattle pens have been increased in size to make improved pens, in which stalks and stover from crops are thrown, trampled, and mixed with manure to form compost (Landais & Lhoste 1993).[10] Different types of compost preparation techniques observed in southern Mali vary in their nutrient value, from (i) compost from an improved pen (Figure 1g), (ii) manure (*poudrette*) from an indigenous pen (Figure 1c), (iii) household compost, (iv) field compost, through to the simplest (v) garbage pile (Blanchard et al. 2013). Among these, garbage piles, indigenous pens, and improved pens are popular practices in Boidiè Commune (Dembélé et al. 2000).

Litter as bedding in pens can prevent inorganic and organic N losses by volatilisation and leaching, and nutrients contained in urine are retained by up to 80% (Nzuma & Murwira 2000). Bedding can also prevent ailments such as sore feet, rubbed necks, and swollen hocks. In the central Kenya Highlands (mean annual rainfall about 1,100 mm), the use of bedding with organic materials in an open kraal (*boma*) is a popular practice; 69% of the sample farmers used bedding materials, such as maize stover, banana residues, grass, and others (Lekasi et al. 2003). In southern Mali, 8–16% of the sample farmers added crop residues to cattle pens as bedding (i.e. improved pens; Blanchard et al. 2013). The improved pen with a crop residue bedding material is sporadically seen around Siakabougou (Figure 1g). However, no bedding techniques using the uneaten grasses available in grasslands, such as *n'gassan* (*Loudetia togoensis*) and *yayalen* (*Andropogon pseudapricus*), were observed.

In mid-September, when many *du* move their daytime grazing area and night pens from *Fúga-ba* to somewhere closer to their hamlet, *Fúga-ba* has abundant unpalatable matured-longgrass left uneaten by animals (Figure 1f). These unpalatable longgrasses can be utilised as bedding materials for the night pens and compost preparation.

Mukai (2019) conducted preliminary action research to develop innovative SFM practices in Siakabougou in 2010 and 2011.(11) Cattle compost preparation with unpalatable matured-longgrass bedding techniques from 2 cattle pens was compared with the local cattle manure preparation method from 2 indigenous pens. No chemical composition (pH, N, P, K, C, and C:N ratio) showed significant differences in contents. The quantity of manure per cattle head-day (capital productivity) derived from the longgrass bedding techniques increased by 67% (4.4 to 7.4 kg $head^{-1}$ $day^{-1}$), while nutrient availability per head-day increased by 6–59% (57.2 to 88.4 g $head^{-1}$ $day^{-1}$ for N, 6.6 to 6.9 g $head^{-1}$ $day^{-1}$ for P, and 21.9 to 35.0 g $head^{-1}$ $day^{-1}$ for K). The quantity of manure and nutrient availability per labour requirement (labour productivity) from the longgrass bedding techniques increased by 38% (17.5 to 24.1 kg $person^{-1}$ $hr^{-1}$) and −15–32% (229 to 288 g $head^{-1}$ $day^{-1}$ for N, 27 to 22 g $head^{-1}$ $day^{-1}$ for P, and 87 to 115 g $head^{-1}$ $day^{-1}$ for K), respectively. The increasing rate of capital productivity was more than that of labour productivity. Thus, the longgrass bedding technique increases the quantity of manure and nutrient supply by inputting more labour force on a limited capital input basis (i.e., labour-intensive technique; de Ridder et al. 2004; Aune & Bationo 2008). The proposed unpalatable longgrass bedding technique can satisfy the requirements for the innovative technologies introduced in agricultural intensification from millet- and sorghum-based low-productivity agriculture (Aune & Bationo 2008).

Even if the quantity and quality of cattle dung left in *Fúga-ba* night pens (*poudrette*) were not currently appreciated and left unused, these would be useful for making household compost and field compost. Household compost and field compost were important sources of organic fertiliser for small farms in southern Mali, providing 49% and 1–22% of the total organic fertilisers, respectively (Blanchard et al. 2013). Compost production is strongly affected by the possession of donkey carts (Bodnár 2005). Accordingly, 80% of the Siakabougou *du* owned at least one donkey and a cart. Because all the *Fúga-ba* pens are over 2 km from the crop fields, lack of access to carts would limit the ability to make field compost using untapped dung left in the *Fúga-ba* pens. In southern Mali, farmers lacking transport or animal dung make field compost with only crop residues in a pit or next to the field (Bodnár 2005). Alternatively, household compost using the hamlet tube-wells as a stable water source in the dry season may be a more realistic option.

## Conclusion

In Sudano-Sahelian Mali, a widespread ring-like organisation of land and soil management has recently been transferred. Farmers may still refer to home and bush fields (*soforo* vs *kungoforo*; Table 1), but permanently cultivated crop fields now replaced previous fallow fields in a bush ring. The landscape is now sharply dichotomised into two components: a compound ring and the surrounding forest/savanna ring for grazing. However, the determinants and rationales of the cropping sequences and SFM strategies commonly seen in the ring management systems in the Sudano-Sahelian and its surrounding zones were still consistently observed. The soil fertility of the four different crop fields in Siakabougou was maintained at a minimal level by different SFM practices under which the local kinship groups, *du* and *gă*, played a vital role. The current SFM practices, mainly composed of manure (*poudrette*) or compost application from indigenous or improved pens and corralling in the dry season, were integrated with diversified cattle grazing and transhumance patterns. The locations of watering sources and palatable pasture grasses and the SFM strategies of the cattle herd manager were the significant determinants and rationales of cattle management patterns in the study area.

Two factors appear essential to meet the growing need for crop production in Sudano-Sahelian Mali. One is to use currently untapped organic resources in the village territory for compost feedstocks; e.g., unpalatable matured-longgrass left in *Fúga-ba* and unused cattle dung (*poudrette*) left in *Fúga-ba* night pens from the peripheral forest/savanna rings. Another is to introduce the varieties of improved pen and compost preparation techniques observed in southern Mali. Specifically, (i) the unpalatable matured-longgrass bedding techniques in improved night pens and (ii) household compost and field compost preparation techniques using the long grasses and *poudrette* will be the candidates for intensified cattle manure management techniques in the Sudano-Sahelian Mali.

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## NOTES

(1) Defining livestock of 250 kg live weight (almost equivalent to a camel in tropical areas) as 1 TLU (tropical livestock units), various livestock is converted to TLU according to their average live weights. TLU is convenient for estimating dry feed weight consumed by various livestock. Cattle = 0.8 in TLU, camel = 1.0, goat and sheep = 0.15, etc., are internationally used in SSA countries.

(2) *Du* is an extended family, while *gă* is an aggregate of plural households of brotherhood. Many numbers and small areas of *gă* fields probably reflect this situation.

(3) The production system in the Sudano-Sahelian Mossi in the 1960s had a smaller number of production units and more homogeneity in cultivation patterns, thus making the village appear like a single production unit with well-delineated cultivation rings. Central (Sudano-Sahelian zone) to southern (Sudanese zone) Burkina Faso experienced rapid population growth due to massive migration from the north and central regions of the country. That increased the population density of southern Burkina Faso from 17 persons km$^{-2}$ in 1986 to 30 persons km$^{-2}$ in 2006 (Ouedraogo et al. 2010). At the time, Sudano-Sahelian Mossi and Sudanese Mossi had about 90 and about 100 persons km$^{-2}$, respectively (Prudencio 1993). Increasing population pressure and greater integration into the market economy have changed the production system. Farm surveys in several areas of Burkina Faso suggested that the cultivation patterns adopted by individual households remain consistent with the ring cultivation concept, with the household compound as the central point of the rings (Prudencio 1993). Thus, the ring management system is typically seen at a household level in Burkina Faso. In contrast, the system can be observed in an extended family, *du*, in the Sudano-Sahelian Mali. Prudencio (1993) surveyed two agroclimatic zones of the Mossi plateau (Sudano-Sahelian zone and Sudanese zone). In each zone, they found three main radial rings stretching from the compound over the crop field: inner, intermediate, and outer. These three radial rings in Mossi overlap the concept of a distinction between compound and bush rings in the West African Sahel. However,

the boundaries of the three rings may not necessarily agree with those of compound and bush rings. Thus, this section used the terms inner, intermediate, and outer rings following Prudencio (1993).

(4) The distances from the *du* or *gă* night pens to the fields also showed no differences between the home (*soforo*) and bush (*kungoforo*) fields.

(5) Oluwalosin (2005) set five land suitability classes (highly suitable, moderately suitable, marginally suitable, currently not suitable, and permanently not suitable) for cereals (millet and sorghum), pulses (cowpea), and groundnuts cultivation in semi-arid northwestern Nigeria. Compared to these criteria, pH ranked highly suitable, but other chemical properties ranked as not-suitable classes.

(6) These unpalatable matured-long grasses are commonly used for thatching when matured and dried.

(7) Mossi farmers use animal manure, pig, sheep, goat, cattle, donkey, and chicken. However, most Mossi farmers prefer to entrust their cattle to herders of the Peulh, except for draft oxen; much manure is away from the area (Bonkian 1982).

(8) Early-maturing maize has 90–95 days, and extra-early-maturing maize hybrids have 80–85 days for maturity periods in SSA (Badu-Apraku & Fakorede 2017).

(9) Matlon (1980) surveyed two Sudano-Sahelian Mossi villages in 1980. Of 44 households interviewed, 21 owned donkey- or oxen-drawn plough implements and 15 owned donkey carts. Batterbury (1996) observed in the Sudano-Sahelian Mossi that less fertile lands were manured, writing, "he/she might borrow or rent a donkey cart, picks, or shovels from a friend."

(10) An improved pen was introduced in southern Mali during the 1990s by the agricultural extension of CMDT. In southern Mali, the improved pen was practised only by the large farms with transportation equipment (donkey carts) in the 1990s; however, it is nowadays done by smaller farms with less material (Blanchard et al. 2013).

(11) The number of samples for both techniques is limited. Besides, this field experiment was conducted in only one village. The feasibility of this improved SFM technique, even in the Sudano-Sahelian Ségou, needs further verification.

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