

Discussion Paper

Manure, Nutrients, and Land Constraints in Sahelian Crop-Livestock Systems: Quantitative Insights for Integrated Soil Fertility Management



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Manure, Nutrients, and Land Constraints in Sahelian Crop-Livestock Systems: Quantitative Insights for Integrated Soil Fertility Management

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1 Introduction

Historically, livestock systems have dominated the Sahelian landscape as these systems are well adapted to the predominant harsh climatic conditions characterized by limited rainfall and high temperatures. Livestock herds move with seasonal rainfall patterns that determine feed and water availability, thereby using biomass on land that is not in use (and often unsuitable) for crop production. In the rainy seasons livestock herds move to the north of the Sahel, where natural rangelands produce limited but high-quality feed; in the dry seasons they move southward, where it is wetter, more crops are grown, and crop residues are available for feed (Bremen and De Wit, 1983; Penning de Vries and Djitéye, 1982). Though low in quality, the crop residues and other scarce biomass resources (e.g., herbs, forests) provide sufficient feed for livestock to survive the dry season, after which animals move northward again when the rainy season starts. This cyclical system based on moving animals over long distances to make best use of the spatially available biomass feed resources has worked for ages. Its benefits for using scarce biomass resources optimally is well understood (Bremen and De Wit, 1983). Pastoral mobility has enabled herders to track spatial and seasonal variation in feed and water resources, but its effectiveness depends on negotiated access to grazing areas, crop residues, water points, and livestock corridors.

With the rapidly increasing population in the Sahel and the corresponding growth in animal numbers and expansion of crop areas (Figure 1), this traditional system of migratory livestock production is under strong pressure and is becoming increasingly constrained.

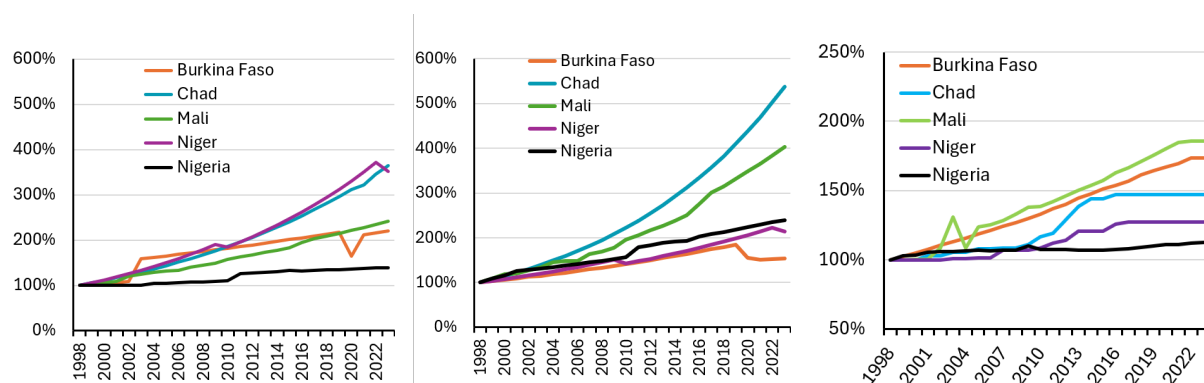


Figure 1. Development of the number of cattle and buffalo (left), number of sheep and goats (center), and the cropland area (right) in selected countries in the Sahel (1998=100%; period 1998–2023). Source: FAOSTAT¹.

There is increased competition for land resources, and conflicts between livestock herders and crop producers are on the rise (Réseau Billital Maroobé, 2021). Traditional rainfed farming in bush-fallow systems based on the natural fertility of the soil and long-term fallow periods is increasingly

¹ <https://www.fao.org/faostat/en/#data/QCL> [visited July 28, 2026].

being replaced by permanent cropland systems (Brink and Eva, 2009). The mobility of pastoralists requires access to feed and water resources, which is increasingly blocked by the expansion of cropland, mining, and urbanization (Brink and Eva, 2009; Güneralp et al., 2017; Herrmann et al., 2020). Cattle routes are attractive sites to farm because of the deposited manure by transhumant herds, and old cattle routes enabling livestock mobility are now becoming too narrow or are even disappearing. These land use developments, alongside expanding statutory land claims and changing local authority over grazing corridors and shared resources, reflect the weakening, transforming, and contesting of customary land governance systems. At the same time, government policies increasingly aim at curtailing livestock mobility and promoting the settlement of pastoralists and the integration of crop and livestock production (Réseau Billital Maroobé, 2021).

Crop-livestock integration affects manure availability, nutrient cycling, crop residue use, fodder supply, livestock productivity, and soil health. Therefore, crop-livestock integration is one of the key themes addressed in the context of Integrated Soil Fertility Management (ISFM) by the Soil Values program in the Sahel. When discussing the role of crop-livestock integration in the Sahel, it is important to gain quantitative insight into the potential role of animal manure and its nutrients for cropping systems and to assess the potential role that cropping systems have in producing feed (crops) for animal production. Although crop-livestock integration is widely promoted as a pathway for improving soil fertility in the Sahel, its practical contribution depends on the quantity of manure that can realistically be produced, collected, transported, and applied and on the land and feed resources required to sustain livestock. These constraints are often discussed qualitatively but are rarely quantified in ways that can guide program design.

1.1 Research Questions and Objective

Considering these land use developments in the Sahel, relevant questions arise: How much manure and nutrients are available for crop production in the Sahel? How much natural rangeland for animal feed is needed to produce sufficient manure for fertilizing cropland? How much manure is needed to maintain soil organic carbon (SOC) stocks of cropping systems? What feed crops are promising to increase animal production? What is the expected increase in animal productivity through better crop-livestock integration?

The objective of this discussion paper is to **provide quantitative insights into the relationship between crops and livestock with a focus on ISFM for identifying options to improve manure use in cropping systems**. We present first-order estimates of manure and nutrient excretion by animals and associated rangeland requirements and the carbon (C) and nutrient requirements of cropping systems in the Sahel. We then explore potential feed crops and their contribution to increasing livestock production and improving manure quality.

Because the Sahel is large and spans different agroecological zones, the estimation methods employed here are based on general calculation rules using average data from literature combined

with rule-of-thumb assumptions. The estimates are intended to identify the order of magnitude of manure, nutrient, C, and land constraints rather than provide site-specific prescriptions. Quantitative estimations are a simplification of reality as there are spatial and temporal differences in resource quantities and qualities and management in the Sahel that determine resource use efficiencies and thus the outcomes of calculations. The estimations aim to get the right scale of figures to improve understanding of crop-livestock systems. Insight into a system's functioning helps to identify interventions and supports interdisciplinary communication among agronomists, soil and livestock scientists, economists, extension services, and policymakers associated with the Soil Values program. By clarifying the scale of manure, nutrient, C, and land requirements, the paper supports Soil Values programming and the dialogue among these individuals and institutions.

1.2 Reader's Guide

Section 2 quantifies the manure and nutrient excretion of animals and crop nutrient requirements. First, crop nutrient requirements are estimated (Section 2.1), followed by manure production and required grazing rangeland (Section 2.2). This information is used to estimate the amount of manure needed to maintain current SOC levels (Section 2.3) and the number of animals and the rangeland area needed to meet crop nutrient requirements (Section 2.4). The total rangeland area needed is compared to the total cropland area in various Sahel countries to assess whether sufficient rangeland is available (Section 2.5). Finally, the estimates presented in the previous sections are compared with other estimates from the literature (Section 2.6). Subsequently, Section 3 addresses the broader role of manure in ISFM and introduces the 4R Framework as a knowledge component to apply synthetic fertilizer and organic nutrient resources according to the best agronomic insights. Section 4 describes options to improve manure use efficiency in cropping systems, and Section 5 describes options to improve livestock productivity through improved crop-livestock interaction. Finally, Section 6 summarizes the major conclusions and gives some general recommendations.

2 Can Crop Nutrient Requirements Be Met by Animal Manure?

To answer the question of this section, we estimate the following variables:

1. Crop nutrient (nitrogen [N] and phosphorus [P]) requirements at current productivity level (Section 2.1).
2. Animal manure (nutrient) excretion and associated rangeland requirements (Section 2.2).
3. Number of animals and the rangeland area needed to meet crop nutrient requirements (Section 2.4).
4. Estimation of rangeland-cropland ratios in selected countries of the Sahel (Section 2.5).

In addition, we calculate how much organic C in the form of manure is needed to maintain current SOC levels of a typical soil in the Sahel (Section 2.3). Crop nutrient requirements are closely related to SOC, which is one of the factors that determine nutrient use efficiencies. Depleting SOC has overall negative consequences for soil health and fertility. Last, we compare the outcomes of our calculations with what the literature has published about this theme (Section 2.6).

2.1 Crop Nutrient Requirements

We limit our analyses to N and P, the most important nutrients in crop production. The parameters used and calculation of variables are shown in Table 1. The N and P requirements are based on current productivity levels of cereals in Burkina Faso, Mali, and Niger. Yields of maize, sorghum, and millet in these countries vary between 0.5 and 2.5 mt/ha; here we assume an average yield of 1.5 mt/ha. We further assume a harvest index of 0.35, dry matter (DM) content of 87%, nutrient concentrations of maize, and 80% of the crop residues are harvested.

Table 1. Calculation rules, assumptions, and data used to estimate the nutrient (N, P) requirements of a cereal crop.

Parameter # (P)/ Variable # (V)	Unit	Value	Remarks and Assumptions	References
P1: Crop yield	mt	1.50 (0.5–2.5)	Range based on three cereals in Burkina Faso, Mali, and Niger.	FAOSTAT (2022) ^a
P2: DM grain	%	87	For maize.	Ludemann et al. (2024)
P3: N content, grain	%	1.59	For maize.	Ludemann et al. (2024)
P4: P content, grain	%	0.29	For maize.	Ludemann et al. (2024)
P5: Harvested crop residues	%	80	Majority will be harvested or grazed.	de Ridder and van Keulen (1990); Roy et al. (2003); Tittone et al. (2008)
P6: N content, crop residues	%	0.76	For maize.	Ludemann et al. (2024)
P7: P content, crop residues	%	0.17	For maize.	Ludemann et al. (2024)
P8: Harvest index		0.35	Typically, between 0.3 and 0.5, but under poor growing conditions, it can be <0.3. Old varieties are at the lower end of range.	Folberth et al. (2012); Ludemann et al. (2022)
V1: N uptake, harvested grains and residues	kg N/ha	35	$= P1 * P2 * P3/100 * 1,000 + P1 * P2 * (1 - P8)/P8 * P5 * 1000 * P6$	
V2: P uptake, harvested grains and residues	kg P/ha	7	$= P1 * P2 * P4/100 * 1,000 + P1 * P2 * (1 - P8)/P8 * P5 * 1000 * P7$	

a. See footnote (1).

Based on the information from Table 1, it is estimated that in each harvest, approximately 35 kg N/ha and 7 kg P/ha is exported from the field in grains and crop residues.

2.2 Rangeland Requirement and Manure Production

In this section, we estimate the collectable amount of manure and nutrients excreted by animals and the associated rangeland requirements. This information provides insight into the potential manure supply (organic matter, C, nutrients) and needs in rangeland to feed animals.

The starting point is the daily average animal DM intake of 6.25 kg per tropical livestock unit (TLU) per day. Furthermore, the average nutrient concentrations of manure (N and P), feed and nutrient intake use efficiency (35% of consumed biomass and nutrients end up in manure), manure collection efficiency (50%), natural vegetation productivity in the Sahel (1 mt DM/ha/year) and grazing efficiency (50%) are important parameters in the calculations.

Table 2. Calculation rules, assumptions, and data used to estimate the amount of manure and nutrients (N, P) produced per TLU and the rangeland area needed to produce manure.

Parameter # (P)/Variable # (V)	Unit	Value (Range)	Remarks and Assumptions	References
P1: Average daily DM intake	kg DM/TLU/day	6.25 (5–7.5)	Generally, DM intake is 2–3% of bodyweight (TLU = 250 kg).	Boudet and Rivière (1968)
P2: Average N content, manure	g N/kg DM manure	17 (13–20)	Average of the range.	Ayantunde et al. (2001); Powell et al. (1995)
P3: Average P content, manure	g P/kg DM manure	2.5 (1.8–6)	Lower end of the range, as values observed in practice are often lower than those reported in experimental studies.	Ayantunde et al. (2001); Powell et al. (1995)
V1: Total DM intake per TLU	kg DM/TLU/year	2,281	= P1 * 365 (days)	
P4: Rangeland productivity	mt DM/year	1 (0.5–2)	Values typical for Sahel region; in Sudano-Sahel, productivity is higher but DM less palatable.	Ayantunde et al. (1999)
P5: Grazing efficiency	%	50	About 50% of produced biomass of natural vegetation is grazed.	Ayantunde et al. (1999)
V2: Grazed biomass	mt DM/ha/year	0.5	= P4 * P5	
V3: Rangeland needed to feed 1 TLU	ha	4.5	= V1/(V2 * 1,000)	
P6: Eaten biomass fraction in manure	%	35 (30–40)	15–20% of eaten biomass ends up in urine, which is difficult to collect or use in crop production unless animals graze the crop residues in the field or are corralled in cropland (which is not assumed here).	Ayantunde et al. (1999)
V4: How much manure is produced	kg DM/TLU/year	798	= P6 * V1	

Parameter # (P)/Variable # (V)	Unit	Value (Range)	Remarks and Assumptions	References
P7: How much of the manure excretion can potentially be collected	-	0.5	During the wet season (three months), manure is too wet to be collected. In addition, collection during 1/3 of the day is also impossible as the cattle are grazing. Hence, $1 - [(1 - 3/12) * (1 - 1/3)] = 0.5$ of the excreted manure is potentially collectable.	
V5: How much manure is potentially available for crop production	kg DM/TLU/year	399	$= V4 * P7$	
V6: How much manure N is potentially available for crop production	kg N/TLU/year	6.7	$= V5 * P2/1,000$	
V7: How much manure P is potentially available for crop production	kg P/TLU/year	1.0	$= V5 * P3/1,000$	

Using the parameters and calculation rules shown in Table 2, on average, about 399 kg DM manure is annually available per TLU that can be used to fertilize cropping systems. This amount of manure contains about 6.7 kg N and 1.0 kg P. To produce this amount of manure, about 2,281 kg DM is consumed per TLU. Using the average productivity of Sahelian rangeland of 1 mt DM/ha/year and grazing efficiency of 50%, about 4.5 ha of rangeland ($= 2,281/[1,000 * 0.5]$) is needed to provide this amount of feed required by one TLU.

It should be emphasized that these calculations are based on feed from rangeland only. Feed based on crop residues does not deliver additional nutrients to cropland; rather, it leads to recycling of nutrients originating from cropland. Moreover, nutrient losses may occur in this recycling process.

The presented estimates differ depending on the assumptions and context of animal herding in the Sahel, particularly seasonality, but they provide a first-order estimate of the magnitude of potential resource demand (feed and land) of animals and supply (manure and nutrients) to cropping systems.

2.3 Organic Carbon and Manure Needs of Soils

Before assessing the number of animals and amount of rangeland needed to meet crop nutrient requirements, this section provides an assessment of the amount of organic C in the form of manure needed to maintain SOC levels. SOC is an important indicator of soil fertility and soil health, and nurturing it is as important for sustainable crop production as supplying sufficient nutrients.

Soil properties, which can widely vary across the Sahel region, largely determine the annual C input requirements to maintain SOC. Here, we estimate the C input requirements (as animal

manure) for sandy soil with a typical low SOC level (0.3%). A first-order estimate of manure requirements for maintaining SOC level of this soil is presented in Table 3. Note that some of the parameters are the same as shown in Table 1 because they relate to the amount of biomass (C) produced by crops that remain in the field after harvest and contribute to SOC.

In the calculations are two important parameters that are relatively uncertain. The first is the SOC mineralization rate. This parameter can vary widely depending on climate conditions, soil type, soil humidity, and (historic) land use management. We used the average mineralization rate (3.6%) as observed in long-term trials in the Sahel (Bationo et al., 2007). Second, the humification fraction of organic material is uncertain. This fraction considers the quality of applied organic material and indicates the part of the applied organic matter that is still in the soil after one year. Lignin-rich materials humify more than sugar- and starch-rich ones, which implies that they resist breakdown and contribute more to stable humus. Materials with a low C:N ratio (N-rich materials) tend to decompose faster, humify less, and contribute less to stable soil organic matter. Humification measurements of manure and crop residues (including roots) under Sahelian conditions have not been found in the literature. A fraction of 0.35 for manure and 0.2 for crop residues has been based on values used in other models applied in sub-Saharan Africa (de Ridder and Van Keulen, 1990; Roy et al., 2003; Tittonell et al., 2008). In general, the organic material in manure is already partly decomposed compared to crop residues. Therefore, the humification coefficient of manure is expected to be higher than that of crop residues.

Table 3. Calculation rules, assumptions, and data used to estimate the amount of organic C as manure that needs to be returned annually to the soil to maintain current SOC of a cropping system.

Parameter # (P)/Variable # (V)	Unit	Value (Range)	Remarks and Assumptions	References
P1: Soil bulk density	g/cm ³	1.5 (1.1–1.7)	Sandy soils, dominant in the Sahel, usually have higher bulk densities than clay soils.	Aina et al. (2019); Loum et al. (2014)
V1: Soil weight, top layer (0–30 cm)	mt	4,500	= P1 * 3,000	
P2: SOC content	%	0.3 (0.25–0.6)		Bationo et al. (2007); Breman et al. (2001)
V2: SOC, top layer	mt/ha	13.5	= V1 * P2	
P3: Annual mineralization rate, SOC	%	3.6 (0.5–7)	Mineralization is high for sandy soils, wet and warm conditions, and high N input; because of a long dry season and little N input, mineralization rates are estimated as moderate. The value is based on the average of 18 long-term experiments.	Bationo et al. (2007)
V3: Annually mineralized SOC, top layer	mt/ha	0.49	= P3 * V2	
P4: Crop yield	mt/ha	1.50 (0.5–2.5)	Range based on three cereals in Burkina Faso, Mali, and Niger.	FAOSTAT (2022) ¹⁾

Parameter # (P)/Variable # (V)	Unit	Value (Range)	Remarks and Assumptions	References
P5: Harvest index		0.35	Typically, between 0.3 and 0.5, but under poor growing conditions, it can be <0.3. Old varieties are at the lower end of range.	Folberth et al. (2012); Ludemann et al. (2022)
P6: Root-to-shoot ratio		0.25	Assumption	
P7: Non-harvested crop residues of total	%	20	Majority of crop residues are harvested or grazed.	
P8: Humification coefficient, crop residues and roots	%	20	Measured data have not been found in the literature. The value is based on values used in other models in sub-Saharan Africa.	de Ridder and van Keulen (1990); Roy et al. (2003); Tiftonnell et al. (2008)
P9: C content, crop residues and roots	%	45	Assumption.	
V4: Non-harvested C, crop residues	mt	0.73	$= \{P4 * [(1 - P5)/P5] * P7/100\} + \{P4 + P4 * [(1 - P5)/P5] * P6\} * P9$	
P10: Humification coefficient, manure	%	35 (27–50)	Measured data have not been found in the literature. The range shown is based on values used in other models in sub-Saharan Africa.	de Ridder and van Keulen (1990); Roy et al. (2003); Tiftonnell et al. (2008)
P11: C content, DM manure	%	25 (15–35)		Ansah et al. (2019); de Ridder and van Keulen (1990)
V5: Required C supply	mt/ha	0.34	$= V3 - (V4 * P8)$	
V6: Required DM supply with manure	mt/ha	3.9	$= V5/P11/P10$	

a. See footnote (1).

Using the parameters and calculation rules shown in Table 3, we estimate that 340 kg C/ha is needed to compensate for annual mineralization losses while the C input from crop residues and roots (that remain in the field) has been accounted for. This corresponds with about 3.9 mt DM manure/ha/year.

Combining these results with those from Section 2.2 shows that about 9–10 TLUs (= 3.9/0.4) are needed to produce the amount of manure required to maintain the SOC content of a typical Sahelian soil. To feed these animals, about 40–45 ha (= number of TLUs * 4.5) of natural rangeland is needed.

2.4 Animals and Rangeland Needed to Meet Crop Nutrient Requirements

Section 2.2 calculated the amount of potentially available manure and contained nutrients per TLU for cropping systems. Here, we combine this information with the nutrient requirements of cropping systems (Section 2.1) to assess the amount of manure and rangeland needed to cover them.

The application of organic manure in cropping systems aims at two major goals: first, to increase the supply of organic matter (C), resulting in improved physical, biological, and chemical soil properties; and second, to increase the supply of nutrients to the crop. These two goals are partly

competing, as the release of nutrients requires mineralization of organic matter in manure, which is thus lost for the formation of SOC stock. In Section 2.3, the amount of organic C in the form of manure needed to maintain current SOC levels in a typical sandy soil in the Sahel has been estimated at approximately 3.9 mt DM manure/ha/year (Table 3).

Considering nutrient-specific recoveries, about 7 mt DM manure/ha for N and 7.1 mt DM manure/ha for P is needed to meet crop nutrient requirements. Considering that about 400 kg DM manure/TLU/year is produced (Table 2), about 17–18 TLUs ($= 7/0.4 - 7.1/0.4$) are needed to meet these crop nutrient requirements; no other nutrients are required. To feed these animals and have them produce the required manure (nutrients), about 76–81 ha ($= \text{number of TLUs} * 4.5$) of rangeland is needed.

Table 4. Calculation rules and data used to estimate the amount of manure needed to meet the nutrient (N, P) demand of a maize crop.

Parameter # (P)/Variable # (V)	Unit	Value	Remarks and Assumptions
V1: N uptake, harvested grains and residues	kg N/ha	35	Table 1.
V2: P uptake, harvested grains and residues	kg P/ha	7	Table 1.
P1: N recovery fraction, manure	%	30	Assumption.
P2: P recovery fraction, manure	%	40	Assumption.
P3: Average N content, manure	g N/kg DM manure	17 (13–20)	Table 2.
P4: Average P content, manure	g P/kg DM manure	2.5 (1.8–6)	Table 2.
V3: Manure needed for N uptake	mt	7.0	$= V1/P3/P1$
V4: Manure needed for P uptake	mt	7.1	$= V2/P4/P2$

2.5 Rangeland-Cropland Ratios in the Sahel

The results of the previous sections show that considerable rangeland and animal resources are required to produce sufficient manure to satisfy the needs of cropping systems, both in terms of SOC and nutrients. Manure availability is a landscape-scale constraint that cannot be solved with changes at farm level only. For example, each hectare of cropland requires around 76–81 ha of rangeland to feed animals to produce sufficient (manure) nutrients. Therefore, it is important to assess whether such ratios of rangeland to cropland are feasible at the landscape level.

Accurate rangeland-to-cropland ratios are lacking because of the difficulty in properly defining rangelands. Using FAOSTAT’s land use categories “permanent meadows and pastures” for rangeland and “cropland” (= arable and permanent crops), ratios are typically <4:1, i.e., for each hectare of cropland, less than 4 ha rangeland is available. Even stretching the definition of rangeland to the entire land area of countries, which is an overestimation of rangeland availability, the ratio is 14 ha of rangeland available to 1 ha of cropland in Mali. In Niger the ratio drops to 7:1,

and in Burkina Faso and Nigeria, the ratio is <3:1. This means that even with an overestimation of the rangeland availability, the ratios do not come close to the required ratio of 76–81:1.

One of the reasons for limited rangeland resources in West Africa is the change in land use over time (Brink and Eva, 2009). Between 1975 and 2013, the area occupied by human-dominated land cover more than doubled from 493,000 to 1,121,000 km² (Herrmann et al., 2020). Based on satellite imagery, the major share of this change could be tracked through the loss of savannas (622,000 km²) and increase in agricultural land (646,000 km²) between 1975 and 2013.

Current ratios of rangeland to cropland are far below what is needed to maintain current soil fertility. These ratios are even less adequate to support the sustainable intensification of crop production, which requires additional nutrients and organic matter and remains the central challenge in the Sahel.

2.6 What Does the Literature Say about Nutrient Demand and Supply for Soils?

The presented calculations are simplifications neglecting the large seasonal fluctuation in feed supply and quality and the spatial differences in resource quantity and quality that affect outcomes in practice. Still, the outcomes are in line with similar exercises published in the literature. Some estimates are more conservative, while others are more optimistic, but all are in the same order of magnitude, i.e., within a factor of 2–10 from the presented estimates.

Powell et al. (1995) summarized published and unpublished data on manure availability for cropping systems in the Sahel. They reported manure collection amounts between 300 and 600 kg per TLU, depending on livestock type, location of the animals, manure production per animal, and the efficiency of manure collection. Our estimate of ~400 kg DM manure per TLU falls well within this range (Table 2).

Williams et al. (1995) compiled nutrient concentrations in manure from different studies in West Africa. Depending on location and animal type, the N concentrations in manure varied between 1 and 2.5% and P concentrations between 0.09 and 0.27% on a DM basis. Nutrient concentrations in manure were 1.7% N and 0.25% P in our calculations (Table 2).

De Ridder and van Keulen (1990) estimated an annual SOC loss of 500 kg/ha/year for the 0–20 cm layer for a typical soil in the Sahel, whereas our estimate for the 0–30 cm topsoil layer was 490 kg/ha/year, using different soil properties (Table 3).

Since N in manure is mainly available in organic form, mineralization of the organic matter is required to make it available for crop uptake. This mineralization process is influenced by soil moisture and temperature and other factors. Commonly, manure N is released during several years after application. Williams et al. (1995) assumed that all nutrients in manure would become

available in mineral form within three years after application, with approximately 50% of the total N released during the first year. Similar to fertilizer N, mineralized manure N is subject to losses resulting in recovery efficiencies below 100%. Therefore, they assumed a recovery efficiency of 30% for manure nutrients. In our calculations, we use an N recovery of 30% and a P recovery of 40% because P is less mobile in the soil and is less sensitive to losses. Both recovery fractions correspond well with the recoveries proposed by Williams et al. (1995).

Additionally, our estimation of the number of animals required to replenish harvested nutrients in maize grains and crop residues, 17–18 TLUs (Section 2.4), aligns well with the numbers found in the literature for other cropping systems. For example, Williams et al. (1995) estimated that between 11 and 23 cattle per hectare of cropland (depending on the crop yield level) are required to replenish N and P in the harvested grains and crop residues. Their estimate of the area's natural vegetation to feed these animals, i.e., 32–129 ha, depends on rangeland productivity and feed management. This range of required land resources is much larger than our estimate (76–81 ha), but we did not include variations in rangeland productivity and feed strategies.

Hence, despite different entry points and assumptions, our estimations are in the same order of magnitude of peers that base their estimates on empirical research.

3 The Role of Manure in Integrated Soil Fertility Management

The analyses in the previous section show that the availability of manure in the Sahel is not sufficient to serve as a bulk nutrient and soil C replacement strategy in cropping systems. Considering the resource limitations of manure, the question arises: What is the added value of integrating crops and livestock?

In integrated crop-livestock farming systems, crop and livestock production interact in such a way that they support and reinforce each other. Benefits associated with integration may also occur between more specialized crop and livestock systems, e.g., through manure and land exchange, though many other potential benefits of integration will diminish or disappear in such cases. Interaction and potential benefits generally relate to three major production factors in agriculture:

1. **Labor:** During land preparation and crop establishment, labor demands are high in situations where fossil fuel-based mechanization is absent. Animal traction substantially reduces human labor requirements for transport of inputs and harvests, enabling farmers to sow timely and cultivate larger crop areas. Animal traction also improves the quality of land preparation, as weed control is more effective and soil mineralization through the soil disturbance is enhanced compared to manual crop planting. Furthermore, animal traction-based tillage alleviates soil crusting problems, which improves water filtration. Integration of crops and livestock within a farming system requires fairly even labor needs since livestock management demands more labor during the dry season while crop management typically requires more labor in the rainy season.

2. **Capital:** Integration of crops and livestock within farming systems diversifies income and spreads both economic and food security risks. Livestock can buffer households when crops fail, and vice versa. In rural areas where formal savings and insurance services are limited, animals effectively serve as both. Traction animals can also be rented out to generate additional income. Moreover, while crop expenditure and income typically come in peaks, livestock provides a steadier cash flow over the year through milk or sales of young stock.
3. **Land:** Livestock converts highly dispersed, low-density, and non-consumable (for humans) biomass from rangelands into food (e.g., milk, meat) and other products (e.g., hides, capital). In addition, grazing livestock concentrates the ingested C and nutrients (not metabolized/respired) into manure that can be used free of charge as nutrient- and C-rich inputs to croplands. In return, cropland not only supplies food and income for farming households but also plays a vital role in feeding livestock. Crop residues, fodder crops, and by-products from post-harvest operations (e.g., threshing, cleaning) provide valuable feed resources, especially during periods when natural pasture is scarce. This creates a mutually beneficial relationship between crop and livestock production.

These three major factors also may result in trade-offs and resource allocation choices between crop and livestock activities, such as in the allocation of labor, capital investments, and crop residue for feed or other purposes. These factors are still in place in sub-Saharan Africa because the process of agricultural mechanization is slow and financial markets are lacking to absorb external shocks and act as savings buffers, while external nutrients and alternative C biomass sources are unavailable or inaccessible for many crop farmers.

The following sections list the benefits of manure for improving soil fertility and show the value of the combined use of manure and fertilizers for crop production in the Sahel.

3.1 The Role of Manure in Improving Soil Physical Properties

Soil organic matter is central to the formation of stable soil aggregates that have a positive effect on several soil properties, including total pore space for improved water infiltration, aeration and gas exchange, and reduced runoff and soil crusting (Haynes and Naidu, 1998).

Hoogmoed et al. (2000) showed that high soil organic matter content improved surface water infiltration of sandy Sahelian soils (Figure 2). Independent of soil moisture conditions, rainfall infiltration increased in soils with a higher C content.

Improved surface infiltration of rainfall contributes to improved water availability for crops in water-limited situations of the Sahel. Therefore, a positive effect of manure applications on increased water availability under Sahelian conditions is likely.

Recently, the extent to which increasing soil organic matter content enhances the water holding capacity of soils has been questioned (Minasny and McBratney, 2018). Based on a meta-

analysis of 60 studies, an increase in soil organic C only showed a limited effect on increasing the soil water content: A 1% (10 g C kg⁻¹ soil, or ~15 mt C/ha) increase in SOC raises the soil water holding capacity by an average of ~1–2 mm per 100 mm of soil. This is much less than the daily crop transpiration in the Sahel. If the SOC of the entire potential rooting zone (~1 m) can be increased by 1%, the total water holding capacity could be raised to a level that supports a few extra days of transpiration. However, typical SOC contents in the Sahel are less than 1% (Breman et al., 2001; Woomer et al., 2004). It has been estimated that a 1% increase in SOC in the 0–20 cm topsoil layer of a typical soil in the Sahel would require an input of more than 30 t manure per hectare (de Ridder and van Keulen, 1990). Increasing and maintaining SOC by 1% across the entire rooting zone will require substantially larger manure amounts or other organic inputs, far beyond the availability of manure and beyond economic viability. The effects of manure and other organic amendments on improving the soil water holding capacity seem to be overestimated in the literature – e.g., Haynes and Naidu (1998); Hudson (1994); Stroosnijder (2009). In much of the literature, the effect of SOC on increasing soil water holding capacity is based on extremely high organic matter inputs or seems to have been confounded with other yield-increasing factors associated with the use of organic amendments, such as improved water infiltration, reduced evaporation (when used as mulch), increased nutrient inputs, or a combination of such factors.

3.2 The Role of Manure in Improving Chemical Soil Fertility

A well-accepted method to investigate nutrient flows in agricultural systems is nutrient balances (or budgets) that are calculated by measuring and comparing nutrient inputs and outputs (Stoorvogel et al., 1993). They can signal a surplus or shortage for sustainable crop production. They also provide information on the order of magnitude of different nutrient flows entering and leaving the system and are thus entry points for improving nutrient management. Generally, the three macronutrients for crop growth – N, P, and potassium (K) – are considered in the balances.

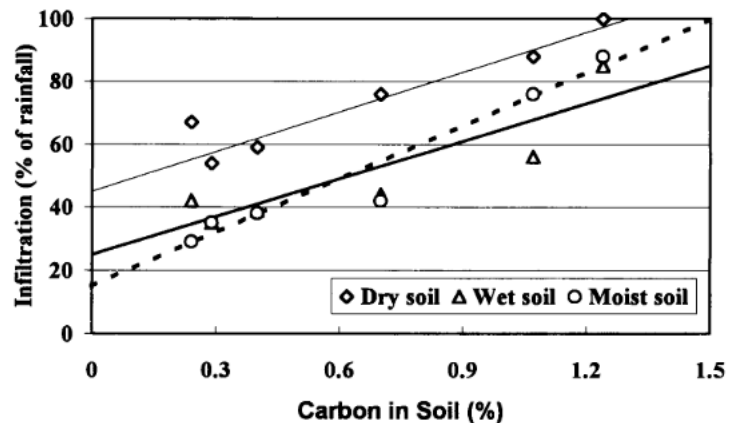


Figure 2. Relationship between soil C content and rainfall infiltration for dry, wet, and moist soil conditions. Source: Hoogmoed et al. (2000).

While an excess of macronutrients represents environmental risks such as nitrate leaching, ammonia volatilization, and nitrous oxide emissions, nutrient deficits indicate soil mining, which may result in soil degradation and lower yields in the future. Key nutrient inputs are synthetic fertilizers, manure, biological fixation, atmospheric deposition, and seed. Key nutrient outputs are crop removals from harvest (grains and crop residues), while other outputs include environmental losses such as leaching, N volatilization, and erosion. Quantification of environmental losses requires location-specific information, which is not always available and therefore is often ignored, resulting in partial nutrient balances.

FAOSTAT estimates national nutrient balances of countries for cropland on an annual basis. These nutrient balances are based on the total cropland in a country, nutrients contained in the harvested crops, total fertilizer and manure availability and fractions applied to cropland, atmospheric deposition, and biological N fixation. Table 5 shows, for illustrative purposes, the N and P balances of croplands for Burkina Faso, Mali, and Niger.

Table 5. N and P balances (in kg nutrient/ha) of cropland in Burkina Faso, Mali and Niger in 2022. Totals may differ slightly from sums because of rounding errors. Source: FAOSTAT (2025)^a

	Burkina Faso	Mali	Niger
Nitrogen inputs			
Atmospheric deposition	4.6	4.5	4.2
Biological fixation	9.2	8.5	4.8
Manure applied	5.1	4.6	2.0
Synthetic fertilizers	6.3	8.0	0.3
Seed	0.6	0.5	1.0
Total inputs	25.9	26.2	12.4
Nitrogen outputs			
Crop harvest removal	23.0	27.6	14.1
Crop residue removal	8.8	13.5	9.3
Leaching	1.7	1.2	0.4
Volatilization	3.4	2.1	0.7
Total outputs	36.8	44.3	24.5
Nitrogen inputs – outputs	-11.0	-18.1	-12.1
Phosphorus inputs			
Manure applied	1.1	0.9	0.4
Synthetic fertilizers	1.4	1.8	0.0
Seed	0.1	0.1	0.2
Total inputs	2.7	2.8	0.6
Phosphorus outputs			
Crop harvest removal	4.5	5.7	2.5
Crop residue removal	1.3	2.9	1.1
Total outputs	5.9	8.6	3.6
Phosphorus inputs – outputs	-3.2	-5.8	-3.0

a. See footnote (1).

Such nationwide nutrient balances are a result of various data uncertainties and assumptions and only give a snapshot in time. They illustrate the relative importance of the various processes and the differences between nutrients, e.g., atmospheric deposition and biological fixation only are

relevant for N. In general, the data of the balances shown in Table 5 support the understanding that the current level of crop production in the Sahel is unsustainable as the nutrient outputs are larger than the inputs (Sanchez, 2002). Equally important to note is that manure still provides a considerable part of the total nutrient input of current Sahelian cropping systems: About 10–20% of the total N input and 33–66% of the total P input is from manure in croplands of Burkina Faso, Mali, and Niger. In many Sahelian cropping systems, P is the most limiting nutrient (Bremen and De Wit, 1983), while P sources other than manure are either not available or not financially accessible for farmers. In addition to being a major source of N and P, animal manure also supplies micronutrients, although quantitative information on its contribution is scarce (Dhaliwal et al., 2019; Traoré and Stroosnijder, 2005).

Animal manure is not only important as a nutrient source for improving chemical soil fertility but also because it improves the soil's cation exchange capacity (CEC), a soil property that quantifies the ability of a soil to exchange positively charged nutrient ions (cations), such as calcium, magnesium, and ammonium (NH_4). Crops take up these cations from the soil solution after they have been released from the exchange sites. These exchange sites are mainly provided by clay particles and especially by soil organic matter in the case of sandy soils. Improving the CEC by manure application is particularly valuable in the Sahel, where sandy, low-activity soils have very limited capacity to retain applied nutrients. Increasing SOC with 0.1% (1 g/kg) resulted in an increase of 4.3 mmol/kg in CEC (de Ridder and van Keulen, 1990). Soils with higher CEC can store more nutrients, buffer fertilizer applications, reduce nutrient leaching, and thus increase the efficiency of applied nutrients.

In general, the application of manure also has a favorable effect on pH by raising the pH of acidic soils. Hence, positive effects of manure applications on the pH can be expected for soil types that are low in pH, in the wetter zones of the Sahel that tend to have more acidic soils, or soils that are low in pH because of intensive and continued use of acidifying fertilizers.

3.3 The Role of Manure in Improving Biological Soil Fertility

Manure contributes to the biological fertility of soils mainly through the provision of feed in the form of organic matter to soil organisms, stimulating biological activity. The organic C in manure serves as an energy source for microorganisms such as bacteria, fungi, actinomycetes, and soil fauna (e.g., especially termites in the context of the Sahel). Increased microbiological activity results in decomposition and release of organically bound nutrients such as N, P, and sulfur (S), which are then available for crop uptake.

Manure can also stimulate arbuscular mycorrhizal fungi (AMF), which form symbiotic relationships with plant roots. AMF can improve P uptake and extend the root system (Bagayoko et al., 2000; Govindarajulu et al., 2005). This functionality is especially important in low-fertility soils, such as in the Sahel. However, moderate P applications are needed in P-depleted soils to stimulate AMF infection and growth. Small doses of animal manure could provide the required P

to kickstart AMF (Ndiaye et al., 2024). However, the relative availability of soil N and P, and whether these nutrients limit plant growth, are determinants of the extent to which AMF colonization benefits plant nutrient acquisition and growth (Johnson, 2010; Johnson et al., 2015).

3.4 Synthesizing the Benefits of Manure for Crop Production

Major benefits of manure for the provision of nutrients and C to cropping systems are well understood and summarized in previous sections. In current Sahelian cropping systems, manure still provides a considerable amount of nutrients (Table 5), and for many arable farmers it is still the main external nutrient and C input. As land use change intensifies and the ratio of rangeland to cropland declines, progressively less manure from ruminants grazing on rangelands is available to fertilize the expanding area of cropland.

The benefits of manure go beyond those of nutrient and C supply, extending to improvements in water capture, soil structure, nutrient buffering, and stimulation of soil microbiology. Not all these benefits are yet completely understood, especially soil biology, which is an under-investigated field of science. The many interactions among biological, physical, and chemical soil fertility properties that come with applying manure are only known to some extent. Therefore, it is still difficult to quantify and predict the outcomes of these interactions. For example, the mineralization of soil organic matter applied with manure is still difficult to capture in simulation models as many factors are involved, including the composition of the organic matter, soil water content, temperature, and soil pH. The lack of knowledge complicates predicting the effect of manure on N mineralization and N availability for crop uptake.

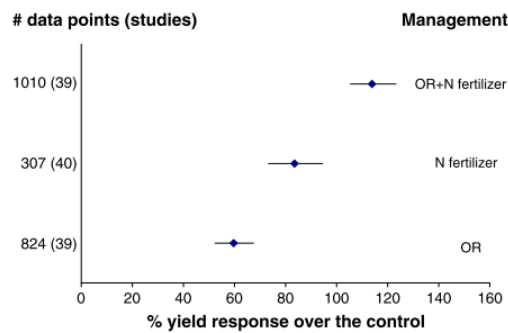
Yet, there is ample empirical evidence of the benefits of animal manure for increasing crop yields (Mando et al., 2005; McIntire et al., 1992; Traoré et al., 2021; Williams et al., 1995). For example, Mando et al. (2005) showed that an annual application of cattle manure (10 mt/ha) over 10 years increased sorghum yields by 56–70% and mitigated SOC depletion. Based on Williams et al. (1995), Table 6 illustrates the relationship between manure application, inorganic nutrient supply, and crop yields in different locations of the Sahel. It shows that manure applied on its own resulted in a grain yield response of 34–58 kg/ha per metric ton of manure across various experiments. When manure is applied in combination with different types and amounts of inorganic fertilizers, the yield response varied between 80 and 90 kg of grain per metric ton of applied manure. However, given the large variation in manure quality, especially nutrient concentrations, generalizations of such results are not possible (Bationo and Buerkert, 2001). Maybe the lower crop response of both treatments with 20 mt manure per hectare compared to 5 mt per hectare in Niger in Table 6 can be ascribed to such differences in manure quality.

Table 6. Results of manure experiments at three sites in semi-arid West Africa. Crop responses are calculated at the reported treatment means for crop yields as: (treatment yield – control yield)/quantity of manure applied. Source: Williams et al. (1995).

Site	Manure	Fertilizer	Crop	Crop Response
	mt/ha	kg/ha		kg DM/mt manure
Mali	10		Sorghum	35
Mali	5	N = 8; P = 20	Sorghum	90
Burkina Faso	10		Sorghum	58
Burkina Faso	10	N = 60	Sorghum	80
Niger	5		Pearl millet	38
Niger	20		Pearl millet	34
Niger	5	P = 8.7	Pearl millet	82
Niger	20	P = 17.5	Pearl millet	32

More recently, Chivenge et al. (2010) carried out a meta-analysis of 57 studies in sub-Saharan Africa where organic resources and synthetic N fertilizers were added separately and in combination. Although the organic resources in this study extended beyond animal manures to include household compost, crop residues, leguminous cover crops, and both leguminous and non-leguminous trees, the study clearly demonstrates the combined effect of synthetic and organic fertilizers on maize yields (Figure 3). The sole addition of organic resources and N fertilizers resulted in 60% and 84% greater maize yields than a control without inputs, respectively (Figure 3a). The combined effect of organic resources and synthetic N fertilizer more than doubled the maize yields (114%) compared to the control. The combined application of organic resources and synthetic N fertilizers increased maize yields by 33% and 17%, respectively, compared to sole application of either (Figure 3b). The greater yield response of combined application was mostly a result of the extra N added. Furthermore, the study showed greater yield responses with increasing quality of the applied organic resources, classified based on N, lignin and polyphenol content, and various other interaction effects, e.g., with soil type and the amount of N fertilizer.

a OR, N, and Combined Treatment vs Control



b Combined treatment vs OR and N fertilizer

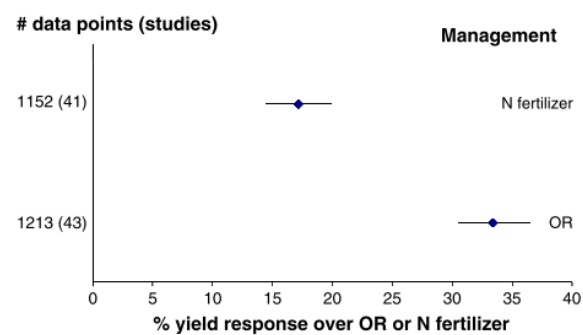


Figure 3. Maize yield response to the application of organic resources (OR), synthetic N fertilizer, and the combination of both (OR + N fertilizer) compared to the control with no input (a), and the combined treatment effect compared to sole N fertilizer or sole organic resources (b). Responses are expressed as weighted average response percentages with 95% confidence intervals represented by error bars. The Y axes show the number of data points and the number of studies from which the points are taken. Source: Chivenge et al. (2010).

According to Vanlauwe et al. (2010), the combined use of organic resources and synthetic fertilizers is one of the components of ISFM. They define ISFM as a set of soil fertility management practices that necessarily include three core components working together: synthetic fertilizer, organic inputs (e.g., manure, crop residues, compost), and improved germplasm (crop varieties), combined with the knowledge to adapt their use to local conditions. The ISFM components are aimed at maximizing agronomic efficiency (AE) and improving crop productivity. AE describes the extra yield of applied nutrient input compared to a control: $(YF - YC)/Fin$, in which YF and YC refer to the yields (kg/ha) in the treatment and the control, respectively, and Fin to the amount of nutrients applied (with synthetic fertilizer and organic sources) in the treatment. Better synchronization of nutrient supply and crop demand in time and space is an important underlying principle of ISFM.

The conceptual relationship among the ISFM components and AE for two types of soils, a responsive soil and a poor, less responsive soil, is shown in Figure 4. Starting from the current practice, the horizontal axis in Figure 4 shows the potential effect of the stepwise implementation of ISFM components on AE. The effect of the ISFM components is shown for both responsive and less responsive soils. The ISFM concept highlights the great effect of the combined application of improved germplasm and fertilizers on responsive soils (Path A in Figure 4). Knowledge is needed about which nutrients are limiting improvements in AE and need to be applied. Furthermore, crops may differ in nutrient requirements, while nutrient management practices may affect the nutrient availability for crop uptake (synchronization supply and demand). When these considerations are accounted for, crop yield and AE may increase considerably on responsive soils.

Path B shows the pathway for less (nutrient) responsive soils, which face constraints other than nutrients, including water shortages and low pH. In contrast with responsive soils, a combined use of synthetic fertilizers and germplasm is much less effective on these soils. However, the combination of improved germplasm, synthetic fertilizers, and organic resources (Path C in Figure 4) is much more effective in increasing AE of these soils compared to responsive soils.

The larger effect of organic resources on poor soils may be related to a combination of different factors, including the (gradual) release of nutrients during the growing period, micronutrients applied with the organic resources, and improvements in soil pH and rainwater infiltration after application of the organic material.

The last step involves the localization of ISFM components, which is expected to have a similar effect on AE in responsive and less responsive soils. Localization includes the awareness and related appropriate actions to deal with the variation in soil conditions, which may be large, even within African smallholder systems (Vanlauwe et al., 2015). It also includes addressing constraints that are not resolved by synthetic fertilizers or organic resources, such as lime applications on acid soils and soil and water conservation measures to reduce runoff and soil erosion.

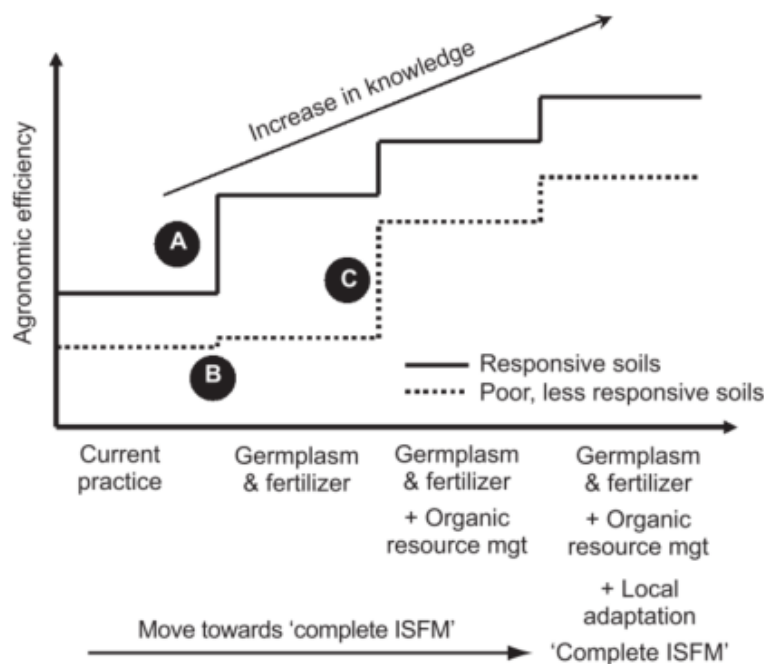


Figure 4. The conceptual relationship between the different components of ISFM and AE. Source: (Vanlauwe et al., 2010).

3.5 The 4R Framework

An important underlying knowledge principle of ISFM is that nutrient supply and crop demand are synchronized in time and space, and ISFM requires in-depth knowledge about nutrient dynamics. To benefit from increased crop yields and AE require the building of agronomic knowledge as indicated by the arrow in Figure 4.

The 4R Framework (right source, right rate, right time, right place) comprehensively describes the knowledge components required to apply synthetic fertilizer and organic nutrient resources according to the best agronomic insights.

Although the 4R Framework was originally developed by the fertilizer industry with a focus on synthetic fertilizers (Johnston and Bruulsema, 2014), it is also applicable in the context of ISFM. The 4R Framework only requires additional knowledge as ISFM addresses the proper combination of synthetic fertilizers, organic resources, germplasm, and local adaptation of nutrient management as the means to improve AE and crop yields:

- **Right Source** – To match fertilizer types to crop needs. Aligns with ISFM’s emphasis on combining synthetic nutrients and organic resources appropriately. For example, a combination of synthetic and organic fertilizers may be most effective on poor, less responsive soils.
- **Right Rate** – To match the amount of fertilizer to crop needs. Supports ISFM’s goal of matching nutrient supply to crop needs and soil fertility status. This requires, e.g., knowing the amount of nutrients to apply with synthetic and organic fertilizers and the amount of nutrients in organic sources that are available for crop uptake.
- **Right Time** – To make nutrients available when crops need them. Complements ISFM practices aimed at the synchronization of nutrient release from both synthetic and organic sources with crop demand. This requires, e.g., knowledge of the mineralization rate of organic matter, which is less predictable (Section 3.4).
- **Right Place** – To keep the nutrients where crops can use them. Reinforces ISFM practices aimed at minimizing losses and improving nutrient uptake, e.g., microdosing and banded application of nutrient sources, considering responsive and less responsive soils (Figure 4).

Within each 4R domain, more specific knowledge needs are apparent (Figure 5). Hence, the 4R Framework provides clear and general guidelines for applying synthetic fertilizer and organic nutrient resources according to the best agronomic insights, but their implementation requires in-depth knowledge of different aspects of the system.

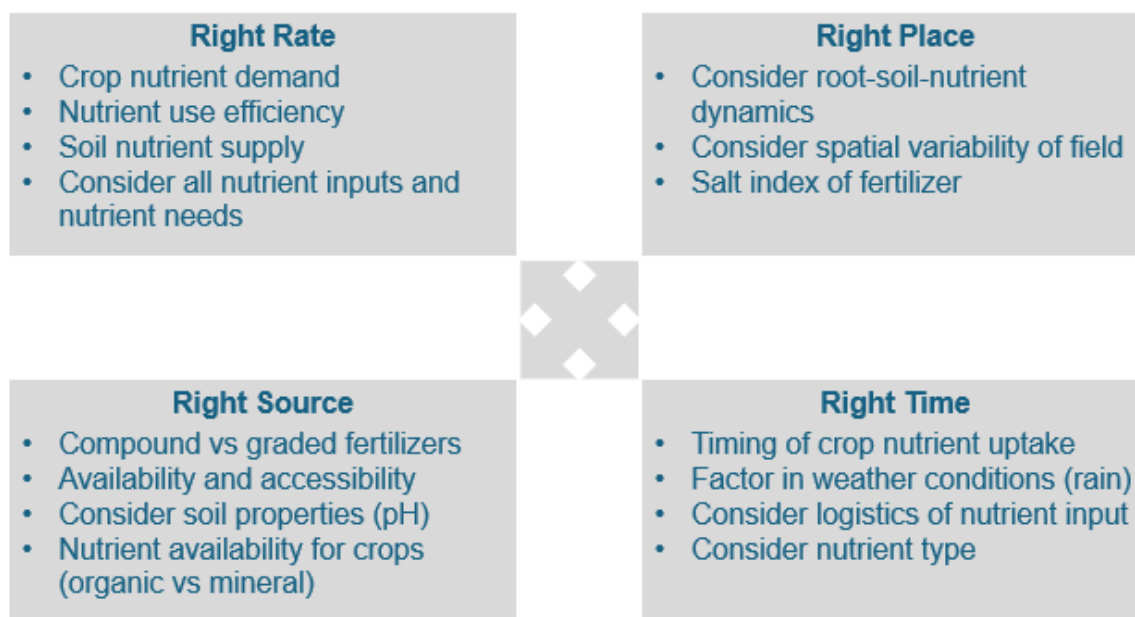


Figure 5. Typical knowledge items in each domain of the 4R Framework.

4 Options to Improve Manure Use Efficiency in Cropping Systems

The previous sections have shown that the contribution of manure to SOC and crop nutrient demand in the Sahel is inherently limited due to resource constraints. Yet, improving manure management at both farm and landscape levels remains valuable. It can enhance fertilizer use efficiency and support increases in crop yields and biomass, including roots and crop residues, thereby contributing to higher SOC. The combined use of manure and fertilizer is a means for using fertilizers more efficiently and therefore is a cornerstone of ISFM (Vanlauwe et al., 2010). Even small amounts of manure can act as a system catalyzer. It remains important to optimize crop-livestock integration to use scarce manure resources efficiently.

Options to improve manure use need to be part of broader crop management strategies, which include proper crop and variety selection (integral part of ISFM, Section 3.4), crop protection, and soil and water management. Although nutrient availability is the main limiting production factor in many parts of the Sahel, water availability may rapidly become another limiting factor once nutrient limitations are solved (Bremner and De Wit, 1983). Soil and water conservation management may improve the water availability for crop production and at the same time preserve soil health and reduce soil nutrient losses. The following options focus exclusively on improving the efficiency of manure use in cropping systems, but other management practices are equally important for improving manure and fertilizer use efficiency.

Options for improving manure use efficiency in crop production can be grouped into strategies aimed at *better allocation of manure* and *reduction of nutrient losses*.

1. Better Allocation of Manure

Options that contribute to this strategy improve *where* manure (and its nutrients) is applied:

- a. Target the use of manure to fields and crops where the expected agronomic and economic return per unit of manure is highest, taking into account transport costs, soil fertility status, and management objectives. For example, the allocation of manure on relatively fertile fields near homesteads reduces labor for manure transport, lowers risks of nutrient losses and product theft, and allows for use in high-value crops. Labor productivity is optimized, while the agronomic return may be relatively low. The use of manure in fields farther away from the homestead with low soil fertility may result in the largest agronomic return. Degraded or sandy soils are often most responsive to manure, but they may require more transport labor. The low-value crops that are often grown on degraded soils may not result in the highest labor productivity. Different objectives need to be balanced in the allocation of manure.
- b. Use spot application rather than uniform spreading to better match nutrient supply with crop needs. This aligns with the *Right Place* domain of the 4Rs. For example, spot application is an element of the Zaï technique, which consists of digging small soil pits to collect water and sediment from surface run-off and adding organic material in the pits before crop sowing (Fatondji et al., 2009).
- c. Improve transport to reduce losses during transport and to reach more distant or responsive fields. Improved transport may also improve the timing of manure application, which reduces losses in the field (Option 2c). This aligns with the *Right Time* domain of the 4Rs.
- d. Provide farmers with decision tools to manage trade-offs in manure use for soil health amendments, energy (e.g., fuel, biogas), construction material, etc., and for the allocation of manure in fields with different soil fertility statuses (Option 1a).

2. Reduction of Nutrient Losses

Options that contribute to this strategy aim at preventing nutrient losses:

- a. Improve manure collection and storage to reduce N losses through volatilization and leaching, e.g., through manure storage in pits or under cover, and to minimize the exposure of manure to sun and rain. Stable feeding animals to facilitate concentrated collection and mix manure with bedding material (crop residues) to accumulate N in C-rich material. This option also includes better manure collection at slaughterhouses.
- b. Conduct composting and manure processing to produce organic fertilizers with more stable forms of C and nutrients that facilitate handling.
- c. Improve timing of manure application to limit losses in the field, e.g., through faster manure transportation (Option 1d) and incorporation until the appropriate time before sowing a crop, so that it is not wasted on unused land. This aligns with the *Right Time* domain of the 4Rs.

- d. Conduct manure analyses to learn what nutrients and how much of each should be applied. This aligns with *Right Source and Right Rate* domains of the 4Rs.

5 Options to Improve Livestock Productivity from Crop-Livestock Integration

Options to improve livestock productivity from crop-livestock integration revolve around enhancing fodder quantity and quality, particularly crop residues; producing optimal combinations of feed resources for efficient use; increasing nutrient cycling and manure use, which will lead to improved soil fertility and associated better grain and fodder (crop residues) yield; and strengthening farmer-herder relations.

5.1 Improved Feed Quality and Quantity

Growing dual-purpose crops such as legumes (e.g., cowpea, groundnut) provides protein-rich crop residues for animal feed and has the potential to add N to the soil. Since the productivity of legumes in the Sahel is often limited by P, the use of animal manure may help to alleviate this limitation (Bationo and Mkwunye, 1991).

The adoption of dual-purpose crops such as cowpea (*Vigna unguiculata*) and groundnut (*Arachis hypogaea*) has been very successful in the region (Kristjanson et al., 2005). These crops provide pulses for human consumption and N-rich haulms (residues) for livestock. Cowpea and groundnut residues are generating considerable business in Sahelian markets, specifically for urban and peri-urban animal fattening (*embouche*) operations (Ayantunde et al., 2014; Sissoko et al., 2024). This situation raises trade-offs in the use of leguminous crop residues, and farmers must choose whether to use the residues for feeding the household animals or to sell them for household revenue.

Studies have shown that supplementing diets of grazing cattle and sheep with millet bran, cowpea hay, or groundnut haulms led to better animal performance (average daily weight gain) compared to those that were not supplemented (Ayantunde et al., 2007; Ayantunde et al., 2000). Without supplementation, grazing steers lost between 50 and 200 g/day during the dry season, whereas those supplemented gained between 60 and 120 g/day. Besides the obvious results of better animal performance by feeding leguminous crop residues along with the basal feeds (e.g., bush hay, cereal stover), optimal feeding levels of crop residues are also important to improve livestock productivity by avoiding feed waste. For example, in traditional sheep fattening in the Sahel, feeds such as cowpea hay, groundnut haulms, and cereal stover are generally provided ad-hoc and in an unregulated fashion, which is rather wasteful. Optimal levels of feeding groundnut haulms (between 300 and 450 g/day/sheep) and cowpea (between 300 and 600 g/day/sheep) for profitable sheep fattening were reported by (Hiernaux and Ayantunde, 2004) and (Ayantunde et al., 2007).

In addition to better animal performance through optimal feeding levels and supplementation with leguminous crop residues, improving the quality of crop residues – particularly cereal stover –

often leads to better livestock productivity (Amole et al., 2022). Options to improve crop residue quality include chemical treatment of cereal stover with urea, physical treatment by chopping and grinding, urea molasses mineral block (UMMB) supplementation, and the use of crop residue mash and multi-nutritional feed blocks. A brief description of crop residue conservation and improvement methods are presented in Table 7.

While maize silage is a staple feed in temperate zones, the Sahelian climate presents challenges: High temperatures can lead to rapid fermentation and spoilage. However, urea treatment of crop residues (such as sorghum or millet stalks) serves as a viable alternative, significantly increasing the crude protein content and digestibility of low-quality roughage.

Improving feed quality, especially toward higher crude protein, will contribute to higher N excretion by ruminants. However, with N intake levels above the requirement of an animal, relatively more N is excreted through urine than feces. Urinary N is mostly urea, which is rapidly hydrolyzed into NH_4/NH_3 , which in turn is prone to volatilization losses. Therefore, most of the urine-borne N will be lost during grazing. Only under corralling in cropland and intensive fattening systems with adequate bedding may some of the higher urinary N excretion be recycled and become available for crop production.

Table 7. Crop residue conservation and improvement methods.

Method	Brief Description	Limitation
Chopping/grinding	Chopping/grinding of fibrous materials increases the surface area exposed to microbial attack and accelerates the rate of the flow of digesta through the gastrointestinal tract, resulting in higher intake of up to 30% more. Chopping/grinding reduces bulkiness and achieves a uniform mix with other crop residues or by-products.	Non-availability of electricity for chopping machines. However, there are locally fabricated manual choppers that do not require electricity. Cost of procuring forage choppers.
Urea treatment	The treatment increases crude protein and energy content of straw, resulting in increased straw intake, growth rate, and the milk yield of the animals. It appears to be a cost-effective technology.	Requires technical knowledge. Low adoption by farmers because of the odor of the urea-treated straw, which often makes the animals reluctant to consume the treated straw.
UMMB supplementation	The UMMB is a strategic feed supplement for ruminants that provides a constant source of fermentable N throughout the day to promote growth of rumen microbes. UMMB supplementation significantly increases feed intake, milk yield, and growth rate, and is therefore a cost-effective approach to maximize the utilization of locally available feed resources for improved productivity.	Cost and availability of molasses.
Crop residue mash	The different ingredients (crop residue and by-products) of the diet are proportioned as per formula to 100 kg batches using appropriate scales.	Poor extension services to train farmers using locally available resources.

Method	Brief Description	Limitation
Strategic supplementation of crop residues with agro-industrial by-products	Enhancing utilization of crop residues, particularly cereal straw, supplementation with agro-industrial byproducts such as bran (of wheat, maize, sorghum) and groundnut/cotton cake may be necessary, depending on production objective.	Availability and price of agro-industrial by-products.
Multi-nutritional feed blocks	Multi-nutritional feed blocks are feed supplements that enhance efficient use of roughages. Ingredients include urea or another N source, roughages (e.g., cereal straw), minerals, molasses (optional), and bonding agents. These ingredients are then weighed to ensure the right proportions, then are mixed, molded, and dried. The blocks can be small (10–20 kg) or large (50–100 kg). Multi-nutritional blocks are for ruminants.	Producing sufficient quantity to meet farmers' demand.

Adapted from Hiernaux and Ayantunde (2004); Amole et al. (2022).

5.2 Efficient Nutrient Cycling and Manure Use

Another option to improve livestock productivity through crop-livestock integration is through efficient nutrient cycling and manure use. Night corralling (kraaling) of animals in cropland to facilitate direct transfer of nutrients from animals to fields while reducing transport needs will enhance recycling of nutrients in mixed crop-livestock systems and improve crop yield and fodder biomass for animal nutrition, which consequently can lead to better animal performance. Another option of improving nutrient cycling is planting legume cover crops (e.g., *Mucuna*), which not only improves soil fertility but also provides high-quality fodder for livestock. Thus, efficient cycling provides a viable option to improve livestock productivity through crop-livestock integration.

5.3 Strengthening Farmer-Herder Relations

Strengthening farmer-herder relations is important for improving livestock productivity in the Sahel to allow transhumant herders access to crop residues for grazing and enable the deposition of manure on the farmers' crop fields. Furthermore, arable farmers may be more interested in growing feed crops or crops producing high-quality residues if trust between farmers and herders increases. Good relations between farmers and herders will not only reduce conflict but will also facilitate livestock mobility and better use of natural resources in communities, especially grazing and water resources. Strengthening farmer-herder relationships may be more difficult in situations of mixed farmers, who raise animals next to growing crops. In such situations, satisfying the feed requirements of their own animals may take priority above trading feed for manure with herders.

5.4 Non-Ruminant Livestock

In the Sahel, the synergy between crop and livestock systems is the cornerstone of sustainable intensification. Poultry systems are rapidly expanding in peri-urban areas and may contribute to increasing manure production for soil fertility improvement. Especially in peri-urban areas, the demand for manure is high in intensive and irrigated cropping systems. However, the greatest

potential for large-scale productivity gains through integration lies with ruminants (e.g., cattle, sheep, goats), which possess the unique physiological capacity to convert fibrous crop by-products into high-value protein and manure (as an organic fertilizer). Animals fed on higher quality diets not only show increased live-weight gains but also produce manure with higher N concentrations that can enhance soil nutrient cycling and crop yields. See also Section 5.1 (Ali et al., 2021; Powell, 2014).

6 Conclusions and Recommendations

Our estimates indicate that maintaining SOC levels (in the 0–30 cm soil layer) of cropping systems in the Sahel requires approximately 3.9 mt DM manure per hectare per year in addition to the C provided with crop residues and roots that remain in the field after harvest. This amount of manure can be produced by about 9–10 TLUs, which in turn requires around 40–45 ha of natural rangeland for grazing. The quantity of manure needed to meet current crop nutrient requirements is even greater, approximately 7 mt DM per hectare. To increase current crop productivity, much more manure would be needed to supply the required nutrients. These figures illustrate the substantial livestock and rangeland resources required to sustain soil fertility in Sahelian cropping systems with manure only. Rangeland biomass availability in the Sahel is insufficient to meet current crop nutrient requirements through feed and manure production alone.

Although the availability of manure is limited in the Sahel, ample evidence from the literature shows that combining manure with synthetic fertilizers is more effective than applying either nutrient source alone. Therefore, manure is an integral component and cornerstone of IFSM. Even small amounts of manure in combination with synthetic fertilizer may serve as a system catalyzer to improve crop productivity.

Manure is a scarce resource in sub-Saharan Africa and thus has an economic value, requiring complex choices about its allocation and incentives for efficient use. Decisions on the use of manure and efforts aimed to increase its availability for crop production require balancing multiple, sometimes conflicting, objectives. Raising awareness and increasing the knowledge of local actors on the value of manure, storage and application methods to reduce nutrient losses, and the associated trade-offs is a no-regret recommendation.

There are various options available to improve the efficient use of manure in cropping systems, from better allocation to reducing nutrient losses before and during field application. In addition, there are options to improve the integration of livestock and crop production that offer win-win situations, e.g., production of high-quality legume feed crops can increase livestock productivity and improve soil health through N fixing. Indirectly, high-quality feed may increase N excretion of animals. Since urinary N is mostly increased, potential benefits of higher N excretion are mostly expected in bedded systems. The suitability and implementation of the identified options to use manure efficiently and to better integrate crop and livestock production is context- and location-

specific. There is no perfect answer, and each option needs to be carefully assessed within the targeted area of implementation.

Optimization of nutrient cycling, including the production of fodder crops in cropping systems, across the livestock-crop domains can reduce nutrient losses from the system. Proper nutrient cycling requires good relationships between arable farmers and herders and can result in mutual benefits. Therefore, improving manure availability and use through better crop-livestock integration is not limited to technical solutions but also may require changes in the socioeconomic and institutional domains.

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