Evaluating the impact of cattle corralling duration on soil nutrient dynamics and sorghum yield in dryland Systems

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Abstract

Livestock corralling is a traditional practice in Sahelian farming systems, yet its contribution to soil fertility and crop productivity remains underutilized. This study assesses the effects of varying corralling durations on manure accumulation, soil nutrient dynamics, and sorghum yield in dryland smallholder systems. A two years field experiments were conducted using 10 Tropical Livestock Units (TLUs) on 150 m² plots across six farms over 3, 7, 10, and 15-night corralling durations. Soil samples and crop performance were evaluated under each treatment and compared to unpenned control plots. Farmer surveys were also conducted to assess perceptions and management constraints.

The amount of dry manure deposited per hectare increased proportionally with penning duration, from 2.82 t ha^{-1} after 3 nights to 14.12 t ha^{-1} after 15 nights using 10 Tropical Livestock Units (TLUs). These organic inputs contributed to marked improvements in soil organic matterup to 34% after 10–15 nights—and a 26% increase in total nitrogen compared to unpenned plots. Longer durations also led to greater accumulation of phosphorus (P) and potassium (K), while soil pH improved from very strongly acidic (pH 4.5–5.5) to weakly acidic levels, especially after 7 nights or more. These fertility gains translated into significantly higher sorghum grain yields, reaching up to 2,651 kg ha^{-1} under 7-, 10-, and 15-night treatments more than 50% higher than the control and 24% higher than 3-night penning. In addition, farmers reported a reduction in mineral fertilizer use by approximately 50% on penned plots, demonstrating the cost-effectiveness and input substitution potential of the practice.

A 7-night corralling strategy offers an efficient balance between labor input and agronomic benefit. Cattle corralling presents a practical, low-cost approach to enhance nutrient cycling, reduce input dependency, and support agroecological intensification in dryland farming systems. Scaling adoption will require context-specific support to address labor, infrastructure, and land access constraints.

I. Introduction

Agricultural systems in sub-Saharan Africa (SSA) are predominantly mixed crop–livestock systems, where crops and animals are closely integrated to support household livelihoods and ecosystem services (Herrero et al., 2010). However, the long-term sustainability of these systems is threatened by severe soil fertility decline, particularly due to the depletion of soil organic matter (SOM), which is a key determinant of nutrient availability, water retention, and overall soil productivity (Lal, 2006).

In many parts of SSA, including Southern Mali, the degradation of cropland is driven by continuous cultivation, minimal fallow periods, and insufficient replenishment of nutrients (Blanchard et al., 2014; Gigou et al., 2004). In the Koutiala region, over 80% of the land is under permanent cultivation and the natural reserves of SOM have steadily declined due to poor organic matter management. These challenges are compounded by widespread poverty and limited access to mineral fertilizers, which together constrain farmers' ability to invest in soil fertility restoration (Kouyate et al., 2021; Ten Berge et al., 2019). As a result, low-input farming systems suffer from declining crop productivity and reduced resilience (Rufyikiri, 2017).

To address these limitations, farmers in the region employ various organic amendments including compost, household waste, and livestock manure to restore soil fertility. Yet, the availability of farmyard manure remains insufficient, covering only 32–60% of crop nutrient needs depending on farm type (Guindo et al., 2024) Given these constraints, practices that integrate livestock more directly into nutrient cycling such as night-time cattle corralling have received renewed interest. Corralling involves confining livestock overnight on cropland, where manure and urine are deposited directly onto the soil, enriching it with organic and mineral nutrients (Ayantunde et al., 2018).

Previous studies have shown that this practice can significantly improve SOM content and increase crop yields. For example, (Bénagabou et al., 2017) reported that organic manure from mixed farming systems in Burkina Faso contributed between 9% and 56% of farmers' manure requirements. Similarly, (Traoré et al., 2014) demonstrated that corralling 20 cattle overnight improved millet yields by 45–106%, depending on the duration of penning. Guerin and Roose (2017) estimate that a single Tropical Livestock Unit (TLU) excretes approximately 25–30 kg of nitrogen per year, with roughly 50% returned to the soil through dung and urine.

However, most existing research have fairly quantified corralling manure contributions and soil impacts in relation to TLU—a standardized metric that facilitates cross-system comparisons. Furthermore, few studies have systematically evaluated how the duration and corralling affect the accumulation of N, P, K, and SOM, and how these changes translate into crop productivity, particularly in cereal-based systems such as sorghum cultivation.

Given these gaps, this study aims to evaluate the impact of cattle corralling (measured by the number of TLUs and duration of overnight penning) on soil fertility and sorghum productivity in the Sahelian zone of Mali. Specifically, the objectives are to: (i) quantify the amount of dry matter and nutrients (N, P, K, organic matter) excreted per TLU during overnight penning; (ii) assess how corralling affects the evolution of soil N, P, K, and SOM content; (iii) evaluate the effect of varying corralling durations on sorghum yield; and (iv) examine the implications of these findings for system-level sustainability in smallholder crop–livestock systems.

II. Methods

2.1. Study site

The study was conducted in Koutiala – in the South-Sahelian zone of Mali, at the villages of N'golonianasso (12°25'37"north, 5°40'59"west), Sirakele (12°31'05"north, 5°28'49"west) and Zansoni (12°35'05"north, 5°36"40'west) from 2019 to 2021. Koutiala zone is characterized by ferralitic, and sometimes ferruginous, deeper, loamy to loamy-clay soils(FAO, 2005) Farming systems are dominated by agro-pastoral production systems based on cotton and cereals (maize, millet, sorghum). In this area, livestock farming is as transhumant as it is sedentary. Manure management practices focus primarily on mineral fertilizer use and organic fertilizer. Manure production is gaining attention as a preferred nutrient-source alternative, although it is hampered by insufficient stocks of crop residues as well as the lack appropriate transport given it is bulky, and time competition for other activities. Composting, animal penning, and household waste generation are the main strategies used to obtain organic manure. Cotton and maize are generally preferred for organic inputs, given the lack of manure and the economic stakes of these crops.

The 2019 and 2020 average annual rainfall in Koutiala fluctuated between 750 and 1000 mm between June and October (Fig. 1). Rainfall amount was 763 mm in 2019 and 936.33 mm in 2020 .

2.2. Quantification and analysis of cattle dung and urine

Quantification of cattle droppings was determined by weighing cattle using a zebu abacus. The TLU conversion table fromMeyer et al. (2022) was used as a reference to convert cattle numbers into Tropical Livestock Units (TLUs). Livestock Standard Unit is a reference weight unit corresponding to a standard 250 kg live-weight cow (Djibo et al., 2018; Vall et al., 2017)The evaluation of the quantities of animal waste excreted per head/night was performed at the agricultural research station in N'Tarla using a head of 17 cattles that included 4 bulls, 3 cows, 3 calves, 2 young bulls and 5 heifers. The collection of cattle dung and urine was done using an isolated box device to confine the animal. The cattle dung excreted overnight was collected in a double-walled bag attached to the animal (Fig. 2). The wet cattle dung was then weighed and then dried in the shade for 7 days then weighed using a precision (0.1g) electronic scale to obtain dry weight.

Urine was collected by isolating the animals in a room with a well cemented floor. The floor was covered with a plastic mat and was laid at a slope and had a gully (small hole) to allow easy flow of urine as soon as excreted. The urine was collected in a container that was hermetically sealed and placed at the back of the room (Fig. 2). The collected urine was quantified for each isolated animal and computed per TLU, per night.

Night corralling and rotation of animals was performed by weighing cattle using the zebu abacus to obtain their weights, and the number of heads corresponding to 10 TLU was determined and the animals were penned. Cattle droppings obtained in each farmer was quantified on the basis of a linear regression equation between chest belt and cattle weight (Dodo et al., 2001; Traore, 2009)as follows:

$$Y = ax + bY$$

Where **Y** is the amount of cattle droppings, **a** and **b** are regression coefficients between the weight of cattle and quantities of cattle droppings, and **x** represents the weight of cattle.

The amount of cattle droppings excreted by TLU/night was calculated according to the duration of overnight penning i.e 3N, 7N, 10N, and 15N.

Cattle dung samples were analyzed for nitrogen (%N), phosphorus (%P), potassium (%K), and organic matter (%OM) using duplicate dried sub-samples (500 g each) obtained from homogenized composite mixtures. Urine samples were collected in the morning via bladder catheterization from cattle designated for penning. Duplicate urine samples (250 mL each) were packaged and analyzed for nutrient content at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) laboratory in Sadoré, Niger.

Soil samples were collected along the diagonal transect of the plots before corralling, and in the various treatments after corralling. Composite samples were pooled based on the treatments and analyzed for N, P, K and soil organic carbon.

2.3. Cattle night corralling and establishment of experimental plots

Experiments on cattle rotation and corralling were conducted with six farmers, with two experimental plots per village. The treatments consisted of varying corralling durations: 3, 7, 10, and 15 consecutive nights, along with two controls (one with Di-Ammonium Phosphate (DAP) application and one untreated control). Each night of corralling corresponded to a 12-hour period (6:00 p.m. to 6:00 a.m.). Each treatment block on a farmer's field was considered a replicate. The selected livestock groups comprised 10 Tropical Livestock Units (TLUs), corresponding to 11–14 head of cattle per farmer. Corralling was carried out during the 2019 and 2020 cropping seasons on fenced plots of 150 m² (15 m × 10 m). Each plot served as an elementary unit for a specific penning duration. Upon completion of each treatment, the wire mesh fence was relocated to the next designated plot (Fig. 3).

As soon as the corralling cycle was completed, soil was ploughting and sorghum (Sorghum *bicolor L Monch*) var."Soubatimi" was sown in the different treatments. The experimental design was a split-plot arranged in a completely randomized block design. The main plot treatments were 4 levels of penning times (3N, 7N, 10N, 15N), while the sub-plot treatments were 3 levels of sowing density (D1 = 0.75 m x 0.20 m; D2 = 0.75 m x 0.30 m; D3 = 0.75 m x 0.40 m) and corresponded respectively to 66,666; 44 444 and 33 333 plants/ha. The DAP treatment received 100 kg ha^{-1} Di-Ammonique Phosphate and no fertilizer application for the control.

2.4. Statistical analyses

Collected data was subjected to analyses of variance (ANOVA) using Genstat 20th edition software, with the application of the Student-Newman and Keuls test at the 5% significance level ($P < 0.05$). Where significant (Prob < 0.05), means separation was performed using SED.

2.5. Sustainability of corralling system according to the length of overnight stays

The sustainability of cattle corralling within a sorghum production system was evaluated using four dimensions: productivity, economic viability, environmental impact, and human well-being, following the framework of Guindo et al. (2022).The contribution of each treatment to these sustainability dimensions was expressed as a percentage. Productivity was assessed based on grain yield, which was further converted into food energy intake. Economic profitability was determined by calculating the gross margin, defined as total income minus total production costs. Environmental impact was assessed through the level of chemical soil pollution, estimated using a partial soil nitrogen balance (($\sum$Input – $\sum$Output).

2.5. Farmers' perception on cattle corralling system.

Individual survey was conducted among 45 farmers in the villages of N'Golonianasso, Sirakélé and Zansoni to collect the farmers' perception of coralling and rotating cattle during the night. Respondents were selected on a voluntary basis and according to their profile as farmers or agro-breeders. The interviews were conducted in the "Bambanankan" language using a translator and focused on the current way cattle pen nights in the fields, the period, the number of penned cattle, the penned area and the duration of rotation. The survey also focused on the target crops of the plots that were penned for the cattles, the manure brought and the constraints related to this practice of rotating cattle.

III. Results

3.2. Quantities of manure and levels of N P, K and OM in cattle dung and urine

Results indicate that cattle age and chest girth are both significantly correlated with live weight ($p < 0.05$). Specifically, each additional year of age was associated with an average increase of 9.343 kg in body weight, while each one-centimeter increase in chest girth corresponded to an average weight gain of 1.398 kg (Table 1). These findings suggest that age and chest girth are reliable predictors of cattle body weight, and the relationship can be described by the following predictive equation:

Cattle weight (*kg) = – 66.6 + 9.343 * age* (*year) + 1.398 * chest girth (cm).*

Table 1
Multiple linear regression of the effect of age and chest *girth* on cattle weights

Variables	Coef	SE	T-Value	P-Value
Constant	– 66.6	40.2	-1.66	0.120
Ages (year)	9.343	0.892	10.48	0.000
Chest girth (cm)	1.398	0.336	4.16	0.001

The nightly collection of cattle dung yielded an average of 1.48 kg of dry matter (dung) and 3.40 liters of urine per Tropical Livestock Unit (TLU). Analysis of the relationship between live weight and manure (dung and urine) indicated a positive correlation, with manure quantities increasing proportionally with cattle weight (Fig. 4). Additionally, a strong linear relationship was observed between the quantities of dung and urine produced (Fig. 5). The prediction of the regression equation is as follows:

*Feces (kg/night/cattle) = 0.4,829 + 0.2,184 * urine (litre/night/cattle)*

The average dry matter (DM) production by 10 TLUs was 14.8 kg of dung and 34 liters of urine per night. Depending on the length of the nights, the quantities of droppings deposited on the penned plots varied significantly (Prob < 0.001). At the scale of the hectare, cattle deposited 2.82 tons and 6.59 tons of cattle dung respectively for the durations of 3N and 7N, while for the 10N and 15N, the deposited corresponds to 9.42 tons and 14.12 tons respectively. Urine excreted also evolved according to the length of overnight stays. For the durations of 3N and 7N, a volume of 6.64 m^3 and 15.48 m^3 of urine was deposited per hectare, against 22.12 m^3 and 33.18 m^3 respectively for the durations of 10N and 15N (Fig. 6).

The amounts of nutrients (N, P, K) and organic matter (OM) deposited through the droppings differed significantly depending on the duration of the penning nights. Organic matter from cattle dung increased from 2.15 t ha^{-1} with the penning of 3N, to 5.02 t ha^{-1}, 7.17 t ha^{-1} and 10.76 t ha^{-1} respectively for the durations of 7N, 10N, and 15N and these quantities were proportional to the duration of penning. Thus, the more the number of penning nights, the higher the amount of organic matter deposited on the penning space. This increasing trend was also valid for NPK analysed from cattle dung and nitrogen from urine (Table 2).

Table 2
Amounts of nutrient elements analysed from cattle dung and urine (kg ha^{-1})

Number of nights	N dung	P dung	K dung	N urine	OM dung
3N	38.17 ± 1.90	15.56 ± 0.78	112.19 ± 5.60	922.89 ± 40.92	2,151.72 ± 107.38
7N	89.07 ± 4.44	36.31 ± 1.81	261.79 ± 13.06	2,153.42 ± 95.48	5,020.67 ± 250.56
10N	127.24 ± 6.35	51.87 ± 2.59	373.98 ± 18.66	3,076.31 ± 136.39	7,172.39 ±,357.95
15N	190.86 ± 9.52	77.81 ± 3.88	560.97 ± 28.00	4,614.47 ± 204.59	10,758.59 ±,536.92

3.3. Quantities of N, P, K and OM from the soil before and after corralling

The ANOVA showed high significant differences (Prob < .001) between the amounts of nutrients (N, P, K, OM) contained in soils before and after cattle corralling. The low stock of soil organic matter (1.03%) before penning (0N) increased by 1.13%, 1.46% and 2.69% with the durations of 7N, 10N and 15N respectively. This increase depicted an average quantity of 45.65 t ha^{-1} for the durations of 10N and 15N, but much higher by 19% when compared to treatments of 3N, 7N, and more than 34% than before penning (0N) (Table 3). The average amount of total soil nitrogen (0.31%N), i.e. 20.83 t ha^{-1} was the same in all corralled plots (3N, 7N, 10N, 15N), but was statistically higher by 23% when compared to those of uncorralled plots, i.e. 0.24% N for control. For phosphorus (P) and potassium (K), except for plots of 10N and 15N having accumulated a similar average quantity of 1.5 t ha^{-1}, the other plots (3N, 7N) have very low levels of these elements, much lower by 67% and 54% compared to 10N and 15N (Table 3).

The soil is a sandy-silty texture, with 62% sand, 25% silt and 13% clay respectively. With cattle corralling soil pH changed from very strongly acidic to weakly acidic soil (Table 4).

Table 3
Quantity (t ha^{-1}) of soil N, P, K and OM before and after cattle penning and soil texture

Average effect of treatments	N	P	K	OM
0N	*14.95*	*0.58*	*0.49*	*30.3*
DAP	15.72	0.6	0.511	31.8
3N	20.16	0.37	0.76	40.1
7N	19.21	0.49	0.75	39
10N	21.89	1.58	1.18	43.2
15N	22.06	1.48	1.55	48.1
Average	19	0.68	1.04	38.8
F.Prob	< .001	< .001	<.001	< .001
S.E.D	1.41	0.17	0.26	3.65
% CV	20.3	68.2	68.5	25.8

Table 4
Soil texture and pH

	Soil texture	*pH before corralling (0N)*	*pH after corralling (7N, 10N and 15N)*
Clay % < 0.002 mm	12.83	4.5–5.5	5.6–6.5
Silt % 0.002–0.05 mm	25		
Sand % > 0.05 to 2 mm	62.17		

3.4. Effect of corralling and seedling densities, stem diameter, plant height, and yield of sorghum

The results indicate that the tallest sorghum plants, both in the year of corralling and in the carryover experiment, were observed under the 7N, 10N, and 15N treatments (Tables 5 and 6). These treatments resulted in plant heights approximately 8% greater than the 3N treatment across both years. The control (0N) consistently recorded the shortest plants, with heights at least 17% lower compared to those under 7N, 10N, and 15N. No significant interaction was observed between corralling duration and seedling density (D1, D2, D3) on plant height during either the initial or the carryover year ($p = 0.875$), suggesting that these factors acted independently. Although a significant main effect of seedling density was detected, it did not interact significantly with corralling duration.

Stem diameter varied significantly with seedling density in both the year of corralling (Table 5) and in the carryover experiment (Table 6). Across all corralling treatments (3N, 7N, 10N, and 15N), the largest stem diameters were consistently observed under the lower seedling densities (D2 and D3), while the smallest diameters were recorded at the highest density (D1). This result confirms a negative relationship between seedling density and stem diameter: as plant density increased, stem diameter decreased (Table 5).

The highest grain yields were recorded under the 7N, 10N, and 15N treatments, which were statistically similar and significantly greater than the yield obtained with the 3N treatment (Table 5). On average, yields under 7N–15N were 24% higher than 3N, while 3N itself produced yields 34% greater than the control (0N).

The interaction between corralling duration and seedling density was not significant ($p = 0.89$), indicating independent effects of the two factors on grain yield. Additionally, there was no significant difference in average grain yield between the corralling year and the carryover year (p = 0.744), suggesting that the beneficial effects of corralling persisted into the subsequent season.

Biomass yield followed a trend similar to grain yield, with the highest values observed under the 7N, 10N, and 15N treatments, which were statistically similar (Table 5). These treatments produced biomass yields that were on average 19% higher than the 3N treatment, which itself was 16% higher than the control (0N).

In the carryover effect experiment, the highest biomass yield (13,044 kg ha^{-1}) was achieved under the 15N treatment (Table 6), representing a significant increase of 10% (p < 0.001) compared to the 7N and 10N treatments, and more than 29% higher than the 3N treatment. The control recorded the lowest biomass production, yielding 47% less than 15N and over 41% less than 7N and 10N.

Table 5

Effect of bedding on plant height, head diameter, stocking density, grain yield and sorghum biomass

Average effect of treatments in 2019 and 2020	**Height (cm)**	**Seedling density**	**Stem diameter (mm)**	**Grain yield kg ha^{-1}**	**Biomass yield kg ha^{-1}**
0N	205.9	85 808	18.29	1 329	8 253
DAP	220.1	82 807	17.81	1 611	9 886
3N	228.2	85 821	18.61	2 003	9 783
7N	243.7	91 642	18.88	2 565	12 044
10N	245.7	93 530	18.8	2 661	11 601
15N	256.3	89 037	19.44	2 728	12 703
Average	233.3	88 108	18.64	2 149	10 712
F.Prob	< .001	0.492	0.685	< .001	< .001
SED	5.95	6 062.50	0.996	134.3	745.4
D1	235.6	119 758	17.16	2 146	10 888
D2	233.5	82 450	18.29	2 126	10 795
D3	230.9	62 114	20.46	2 176	10 452
Average	233.3	88 108	18.64	2 149	10 712
F.Prob	0.54	< .001	< .001	0.872	0.685
SED	4.21	4286.8	0.705	95	527.1
Penning year 2019	240.2	94 614	15.73	2 226	9 644
Penning year 2020	225.1	80 300	22.12	2 058	11 993
Average	233.3	88 108	18,64	2 149	10 712
F.Prob	< .001	0,003	< .001	0.123	< .001
SED	4.06	4 789	0.399	108.4	449.5
*F. Prob corralling duration * densities*	0.875	0.793	0.742	0.895	0.995
*F. Prob corralling duration * years*	0.131	0.477	0.518	0.004	0.012
*F. Prob densities * years*	0.398	< .001	< .001	0.689	0.011
*F. Prob corralling duration * densities x years*	0.961	0.995	0.837	0.956	0.764

Table 6
Carryover effect of treatments on plant height, stem diameter, stocking density, grain and biomass yield of sorghum

Average effect of treatments in 2020 and 2021	**Height (cm)**	**Stocking density**	**Stem diameter (mm)**	**Grain yield kg ha^{-1}**	**Biomass yield kg ha^{-1}**
0N	208.2	94 200	20.143	1 237	6 926
DAP	210	97 467	20.623	2 016	9 119
3N	209.8	96 244	21.511	2 042	9 341
7N	222.7	93 689	22.928	2 501	11 652
10N	225.6	99 956	23.094	2 280	11 811
15N	227	98 689	23.2	2 626	13 044
Average	217.2	96 707	21.917	2 117	10 315
F.Prob	0.002	0.944	< .001	< .001	< .001
SED	6.27	7 132.2	0.3444	227.4	550.7
D1	221.4	133 811	21.241	2 143	10 204
D2	216.9	86 344	21.979	2 118	10 320
D3	213.4	69 967	22.53	2 090	10 422
Average	217.2	96 707	21.917	2 117	10 315
F.Prob	0.2	< .001	< .001	0.948	0.854
SED	4.44	5 043.3	0.2435	160.8	389.4
Rear effect 2020	236.5	86 680	22.74	2 465	11 052
Rear effect 2021	193.12	109 242	20.88	1 682	9 394
Average	217,22	96707	21.92	2 117	10 315
F.Prob	< .001	< .001	< .001	< .001	< .001
SED	1.708	5 659.3	0.249	134.7	434.1
Penning years (2019, 2020)	233.3	88 108	18.64	2 149	10 712
Rear effect (2020, 2021)	217.2	96 707	21.92	2 117	10 315
Average	226.1	91 977	20.11	2 135	10 533
F.Prob	< .001	0.024	< .001	0.717	0.234
SED	2,87	3 781.2	0.357	89.4	332.7
*F. Prob corralling duration * densities*	0.957	0.996	0.997	0.888	0.984
*F. Prob corralling duration * years*	< .001	0.877	< .001	0.004	0.535
*F. Prob corralling duration * years*	< .001	< .001	0.104	0.311	0.8
*F. Prob corralling duration densities * years*	0.965	1.000	1.000	0.920	0.878

3.6. System-level sustainability of cattle corralling

The results show that the control treatment had the lowest contributions across all indicators, with particularly poor performance for the environmental domain, where values were negative (Fig. 7). The application of 100 kg/ha DAP moderately improved productivity and profitability (contributions around 50–60%) but had negligible effects on environmental sustainability which reflects the limited systemic impact of chemical fertilizers when used in isolation.

In contrast, cattle corralling treatments demonstrated significant advantages. The 3-night corralling yielded moderate improvements, especially in productivity and profitability, food security, while contributions for environmental sustainability remained low. More importantly, 7-night corralling showed a clear threshold, with high contributions (~ 90–100%) across productivity, profitability, and food security, and slight improvements in environmental performance. This positive trend continued with 10 and 15 night treatments, though the gains in comparison to 7 nights were marginal, suggesting diminishing returns beyond the 7 night threshold. Across all corralling treatments, improvements in food security closely followed the patterns observed in productivity and income-related indicators, highlighting the interconnectedness of agricultural productivity and household food access. Across, all the treatments, environmental sustainability, while initially low under control and DAP treatments, showed a clear and progressive improvement with increasing corralling duration.

3.7. Farmer's practice of cattle corralling

The results of the survey show variation in cattle penning practices. On average, 30.57 ± 6.87 cattle were penned over an area of 1.18 ± 0.61 ha for approximately 10 ± 2 nights, reflecting the common practice of short-duration rotational penning (Table 6). Penning rates were highest in N'golonianasso and Sirakele (66.67%), while Zansoni had a lower rate (40%), despite a higher number of penned cattle. This suggests that penning intensity is influenced not only by livestock availability but also by land size and farmer management strategies. The observed average penning duration of 10 nights aligns with optimal thresholds identified for improving soil fertility and crop yield, reinforcing its agronomic relevance.

Overall, maize and cotton are the dominant crops grown (Table 6) on the penned plots, with maize occupying 40% of the area and cotton 31% indicating a strategic use of penned plots. Sorghum and millet were not reported as major crops on penned plots, likely due to their lower nutrient demands and common placement later in the cropping cycle, where residual fertility can be exploited. Regarding fertilization practices, the results show widespread use of mineral fertilizers on penned plots that even on organically enriched plots, farmers often complement manure inputs with mineral fertilizers, suggesting a strong reliance on mineral inputs to optimize yield potential following penning.

With regards to farmers perception of constraints related to cattle corralling, results showed that, approximately 29% of respondents found night rotation very restrictive, 22% moderately restrictive, and 30% did not perceive it as a constraint (Table 7), while 61.11% of farmers did not consider watering to be a constraint, compared to only 3.33% and 10% who classified it as very or moderately restrictive, respectively.

Table 6
Farmers practice of cattle corralling

	Corralling statement				**Crops (%)**				**Fertilization (%)**		
Village	Number of penned cattle	Corralling area (ha)	Penning time (overnight)	Penning rate (%)	Cotton	Maize	Sorghum	Millet	NPK cotton	NPK cereal	Urea
N'golonia	26.60	1.88	12	66.67	26	33	-	-	73	73	100
Sirakele	26.60	0.74	9	66.67	40	60	-	-	93	80	100
Zansoni	38.50	0.92	10	40.00	26	26	-	-	80	73	77
Average	30.57	1.18	10	57.78	31	40	-	-	82	75	92

Table 7
Farmer perceptions of constraints related to cattle corralling.

Villages	Night rotation and penning				Watering of animals			
	Very restrictive	Moderately restrictive	Low Binding	No Constraint	Very restrictive	Moderately restrictive	Low Binding	No Constraint
N'golonianasso	30	30	10	30	0	10	30	60
Sirakélé	40	20	30	10	10	20	30	40
Zansoni	16.67	16.67	16.67	50	0	0	16.67	83.33
Average	28.89	22.22	18.89	30	3.33	10	25.56	61.11

IV. Discussions

4.1. Dynamics of manure accumulation and nutrient input in corralling systems

We found that the quantities of dry cattle dung deposited per hectare increased proportionally with the duration of corralling. Using 10 Tropical Livestock Units (TLUs), the quantity of dung recorded was 2.82 t ha^{-1} after 3 nights (3N) and 6.59 t ha^{-1} after 7 nights (7N). This amount further increased to 9.42 t ha^{-1} and 14.12 t ha^{-1} for 10-night (10N) and 15-night (15N) treatments, respectively. These results confirm a strong positive relationship between corralling duration and manure accumulation, consistent with previous studies in the Sahel (Landais et al., 1990; Schlecht and Buerkert, 2004). The progressive buildup of organic material suggests that longer corralling durations enhance the input of nutrients and organic matter into the soil, thereby improving its fertility potential. However, the quantity of manure produced by cattle may vary significantly according to the seasons and the type and quality of feed provided. Seasonal fluctuations in forage availability and feed composition influence both the volume and nutrient content of dung and urine. During the dry season, reduced feed intake and lower-quality forage often result in smaller quantities of manure with lower nutrient concentrations (Rufino et al., 2006; Schlecht and Buerkert, 2004). affecting the efficacy of corralling practices (Rahimi et al., 2020).

Research indicates that livestock corralling can result in uneven manure deposition, creating nutrient-rich hotspots rather than uniformly enhancing soil fertility and may lead to inefficient nutrient utilization and potential environmental concerns (De Deyn et al., 2009). Despite the operational challenges such as labor-intensive nature and logistical demands, cattle corralling presents substantial opportunities for both pastoralists and crop farmers in the Sahelian context. The practice facilitates a mutually beneficial exchange between livestock and cropping systems (Turner and Hiernaux, 2008). Furthermore, corralling also serves as a cost-effective alternative to traditional manure management practices. In many smallholder systems, the collection, transport, storage, and manual application of manure represent significant labor and financial burdens. By concentrating on animals directly on agricultural land, corralling eliminates the need for these steps, thereby increasing the efficiency of nutrient recycling and minimizing nutrient losses associated with storage and handling(Rufino et al., 2006). This implies that longer corralling durations can significantly enhance soil fertility, potentially improving nutrient availability for crops and contribute to long-term carbon sequestration (Giller et al., 2009). Therefore, this practice can offer a practical and sustainable solution to soil nutrient depletion, especially in regions with limited access to chemical fertilizers.

4.2. Soil fertility improvements and sorghum yield response to corralling duration

Our results demonstrate that cattle corralling significantly enhances soil organic matter (SOM), with improvements of approximately 34% observed following 10 to 15 nights of penning, compared to a 19% increase with shorter durations of 3 to 7 nights. This trend strongly suggests that the cumulative quantity of dry matter from dung deposition plays a central role in driving SOM accumulation. The nutrients from the droppings can percolate into the soil due to trampling by animals. The greater deposition of organic inputs over longer penning periods enhances microbial activity and improves soil structure and fertility (Machmuller et al., 2015; Rahman et al., 2019; Rayne and Aula, 2020) particularly in systems where synthetic inputs are limited. Beyond nutrient recycling, the repeated deposition of organic matter enhances soil structure and promotes the formation of stable aggregates, which increase porosity and water-holding capacity which is particularly beneficial in dryland conditions where rainfall is erratic and infiltration is low (Mando et al., 1996).

We found that soil nitrogen (N) content was comparable across all penned plots but was 26% higher than in the unpenned control plots. In contrast, phosphorus (P) and potassium (K) levels in the 3N and 7N treatments were significantly lower by 67% and 54%, respectively compared to those in the 10N and 15N plots. These findings suggest that even short durations of corralling (3 to 7 nights) are sufficient to increase total nitrogen in the soil. This is likely due to rapid deposition of urine, which is rich in readily available nitrogen, and the microbial transformation of organic nitrogen from dung. However, the marginal gains level off with longer durations, possibly due to nitrogen saturation or losses (e.g., through volatilization or leaching) (Sutton et al., 2011).

Unlike nitrogen both P and K are less mobile in the soil and tend to accumulate near the point of deposition (Bationo et al., 2007; Schlecht and Hiernaux, 2004). As a result, longer corralling durations lead to greater accumulation of these nutrients suggesting that to effectively enrich soils with phosphorus and potassium particularly in Sahelian regions where phosphorus deficiency is common, corralling periods of 7 nights or more are more effective, as the gradual buildup of manure enhances nutrient availability over time.

The initial soil pH values across the study area indicated very strongly acidic conditions, ranging from 4.5 to 5.5. Following livestock penning, a progressive increase in soil pH was observed, particularly after 7, 10, and 15 nights of corralling. In these treatments, the soils transitioned from very strongly acidic to weakly acidic, indicating a significant amelioration of acidity due to penning duration.

This improvement in soil pH can be attributed to the cumulative effect of organic inputs principally livestock manure and urine deposited during penning. These organic residues serve as sources of base-forming cations such as calcium (Ca^{2+}), magnesium (Mg^{2+}), potassium (K^+), and sodium (Na^+), which are known to neutralize exchangeable acidity by replacing hydrogen (H^+) and aluminum (Al^{3+}) ions on soil exchange sites (Agegnehu et al., 2016; Haynes and Mokolobate, 2001). In addition, enhanced microbial activity stimulated by the influx of organic matter may further support pH buffering through decomposition processes and the release of humic substances, which improve the soil's capacity to resist drastic pH fluctuations. This finding aligns reports highlighting the importance of consistent organic matter application in modifying soil acidity, particularly in tropical soils where low pH is often a limiting factor for crop productivity due to nutrient unavailability and aluminum toxicity(Vanlauwe et al., 2015). In this context, strategic corralling emerges as an effective, low-cost soil management practice for smallholder systems in acid-prone environments. By improving soil chemical conditions, it can contribute to better nutrient availability.

The benefits of these soil nutrient change (OM, pH, etc) were reflected in sorghum grain and biomass yield, which were significantly higher under longer corralling durations. Grain yields reached up to 2,651 kg ha^{-1} in the 7-, 10-, and 15-night treatments, representing a significant increase compared to the 3-night corralling (yield was less than 24% lower) and the control (more than 50% lower). These results demonstrate a strong correlation between improved soil fertility, especially pH adjustment and organic nutrient inputs and crop productivity (Haynes and Mokolobate, 2001; Vanlauwe et al., 2010). The relatively lower yield under the 3-night corralling treatment suggests that shorter durations do not provide sufficient nutrient accumulation or time for nutrient mineralization to benefit crop growth. Conversely, longer corralling periods likely ensured more uniform and sustained nutrient availability, especially for nitrogen, which increased by approximately 26% in corralling field relative to the unpenned control. The role of improved pH is particularly critical, as low pH can inhibit root growth, reduce microbial activity, and limit the availability of essential nutrients, especially phosphorus and molybdenum (Vanlauwe et al., 2015).

In line with previous research (Powell et al., 2004) the integration of livestock through strategic penning emerges as a viable, low-cost agroecological approach to enhance soil fertility and crop yields. In dryland farming systems, where access to mineral fertilizers is often limited, optimizing the timing and duration of livestock corralling can significantly contribute to soil restoration and improved agricultural productivity.

4.4. *Opportunities and constraints of dry season cattle corralling*

Findings indicate that farmers increasingly recognize the agronomic benefits of dry season cattle corralling. In the Koutiala region, the widespread presence of livestock, especially with medium and large-scale farms, present a valuable opportunity to integrate corralling as a sustainable soil fertility management practice (Guindo et al., 2024). We found that farmers' corralling strategies also influence subsequent cropping choices. In corralled fields, 40% of farmers planted maize and 31% cotton crops commonly positioned at the beginning of crop rotations due to their economic value and capacity to capitalize on the nutrient-rich conditions created by penning. In these plots, no additional organic inputs were applied, and farmers reported reducing mineral fertilizer application by approximately 50% compared to non-penned plots—a finding consistent with earlier research showing that cattle corralling substantially reduces reliance on external inputs (Sangaré et al., 2002; Schlecht and Buerkert, 2004).

Spatial decisions regarding corralling are often influenced by security and labor considerations. Farmers preferentially corral livestock near homesteads to reduce the risk of theft and avoid conflict with transhumant herds. As a result, more distant fields are less likely to benefit from this fertility-enhancing practice. Despite its benefits, these findings emphasize the need for context-specific support measures, including improved penning infrastructure, collective organization for labor-sharing, and better access to water sources, to alleviate the burden on farmers and enhance the adoption of penning practices.

4.5. Systemic benefits of cattle corralling for sustainable intensification

The findings of this study clearly illustrate the systemic benefits of integrating cattle corralling into smallholder production systems. The control treatment, which received no external nutrient inputs, consistently recorded the lowest performance across all indicators, with especially negative values in the environmental domain. This result underscores the well-documented challenges associated with continuous cultivation without nutrient replenishment in the Sahel, where soil fertility depletion remains a major constraint to sustainable production (Tittonell and Giller, 2013; Vanlauwe et al., 2006).

Application of 100 kg/ha of diammonium phosphate (DAP) moderately improved productivity and profitability, with contribution scores around 50–60%. However, it had negligible impact on environmental sustainability, reflecting the limited capacity of inorganic fertilizers, when used in isolation, to improve soil health or ecological resilience (Vanlauwe et al., 2014).

In contrast, cattle corralling treatments demonstrated notable system-wide advantages. The 3-night corralling resulted in modest improvements in productivity, profitability, and food security, though the effect on environmental sustainability remained minimal likely due to limited manure accumulation and uneven nutrient distribution. However, a marked threshold was observed at 7 nights, where contributions across all dimensions particularly productivity, profitability, and food security reached 90–100%, with visible improvements in environmental performance. This suggests a critical duration beyond which nutrient deposition and soil biological processes are sufficiently activated to support systemic gains. These results are consistent with findings by (Schlecht and Hiernaux, 2004), who showed that livestock corralling can significantly improve topsoil quality, nutrient cycling, and organic carbon content when applied consistently and at sufficient intensity.

While 10- and 15-night treatments sustained high levels of performance, the marginal gains beyond 7 nights were limited, indicating diminishing returns. This trend suggests that a 7-night corralling strategy may offer the optimal balance between labor input, nutrient loading, and area coverage. It also opens the possibility of rotating livestock across multiple plots within the dry season to extend benefits more equitably across the farm landscape.

Food security improvements closely mirrored the trends in productivity and income-related indicators, further confirming the strong linkage between agricultural output and household food access (FAO, 2017). Corralling not only enhanced yields but also reduced the need for costly external inputs, thereby improving household-level profitability and resilience (Atakoun et al., 2025).

V. Conclusion

This study provides strong evidence that dry-season cattle corralling can significantly improve soil fertility and crop productivity in smallholder systems of the Sahel. The quantity and duration of manure deposition were directly linked to improvements in soil organic matter, nitrogen content, and pH, with 7-night corralling emerging as an effective threshold for optimizing nutrient inputs and crop response. Sorghum yields increased substantially under longer corralling durations, and farmers reported a reduced reliance on mineral fertilizers.

While 10- and 15-night treatments sustained positive outcomes, marginal gains beyond 7 nights suggest diminishing returns, reinforcing the efficiency of a 7-night rotational strategy. Despite logistical challenges, cattle corralling offers a scalable and cost-effective pathway to agroecological intensification by integrating livestock and cropping systems. These findings underscore its potential for sustainable land management and call for supportive measures to enhance adoption among smallholder farmers in dryland regions.

Declarations

Author Contribution

BT led conceptualization, funding acquisition, validation, and drafting, with all authors contributing to data analysis, writing, and review. MG and HK supported data curation and analysis; BZB, GD, and MM contributed to supervision and editing; and RH managed project administration and resources.

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Figures

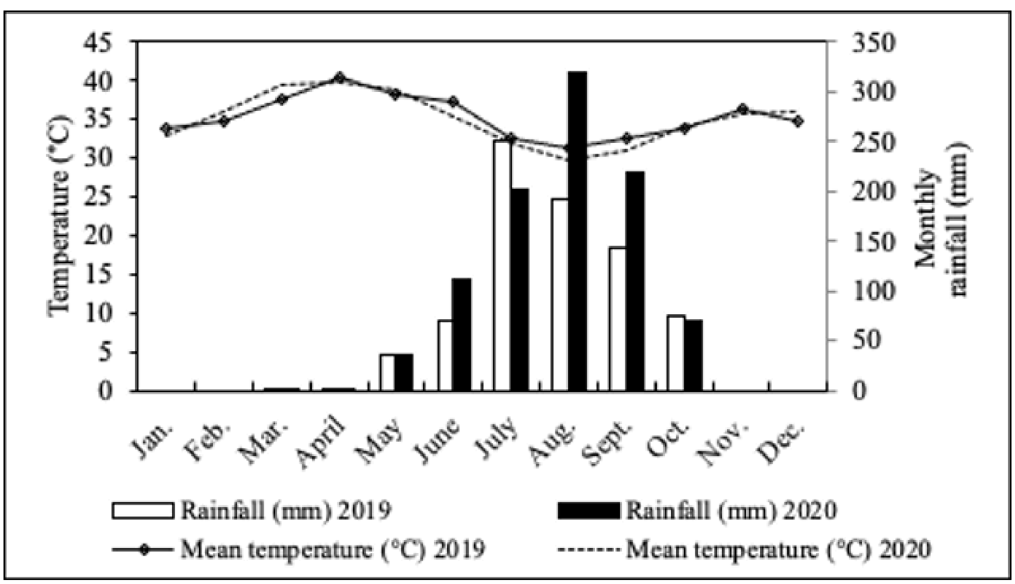

Figure 1

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

Figure 2

Collection and quantification of cattle droppings (dung and urine)

Figure 3

Cattle corralling and droppings deposits over nights

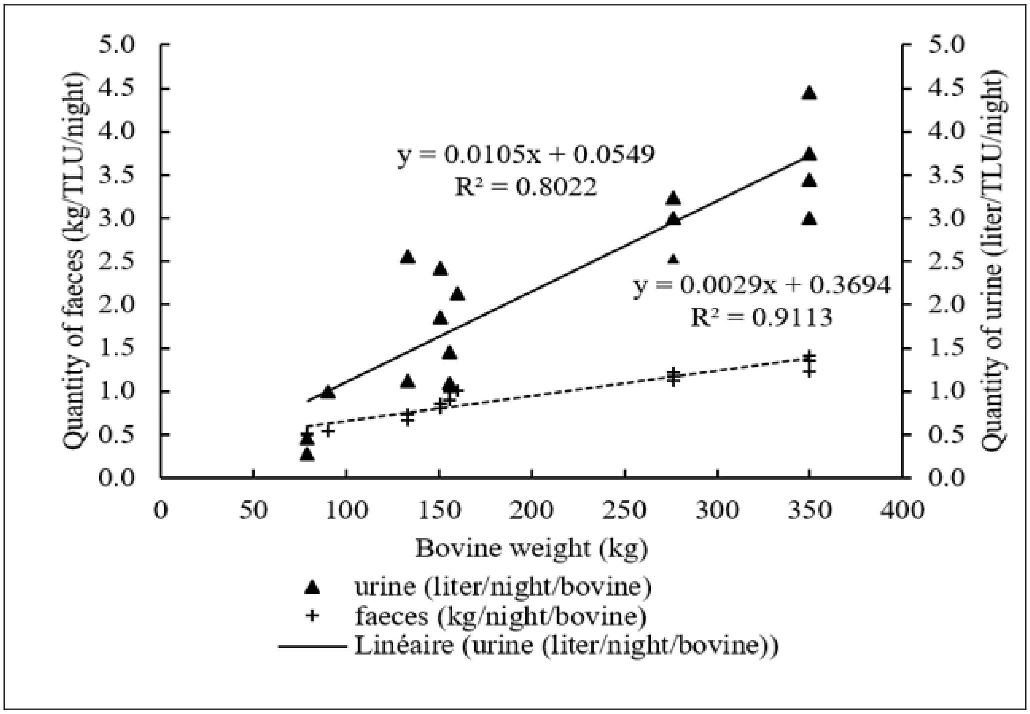

Figure 4

Relationship between cattle weight and amounts of cattle dung and urine excreted

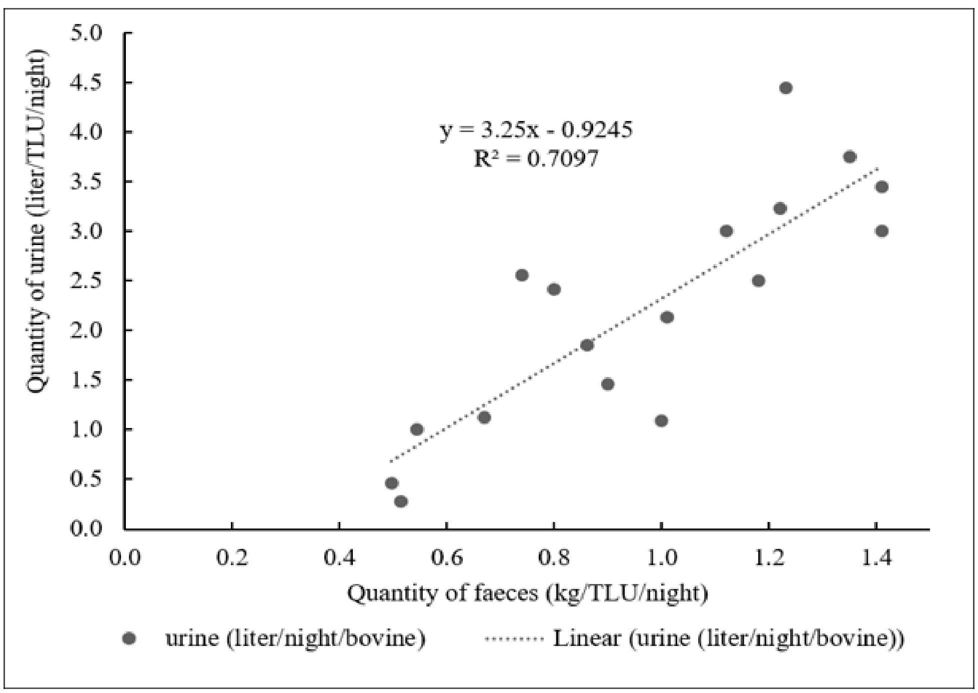

Figure 5

Relationship between amounts of urine and cattle dung excreted

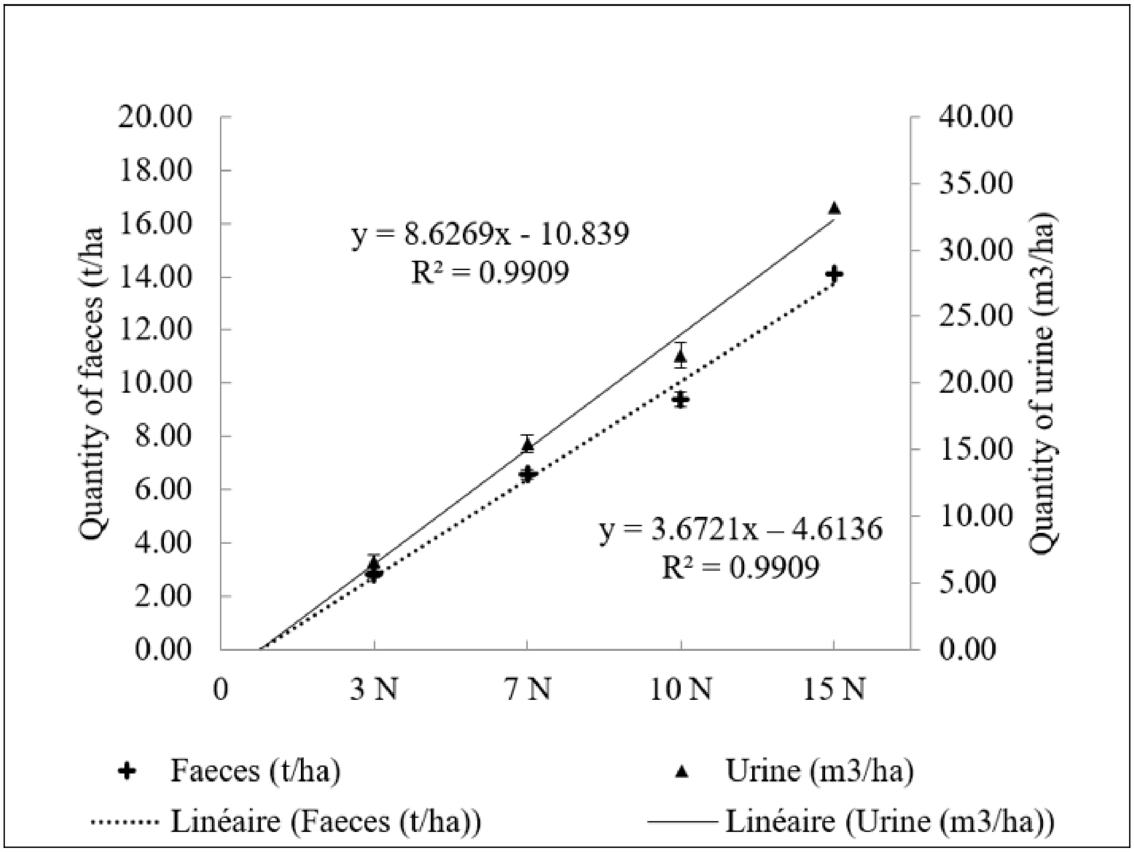

Figure 6

Relationship between quantities of manure excreted over corralling time

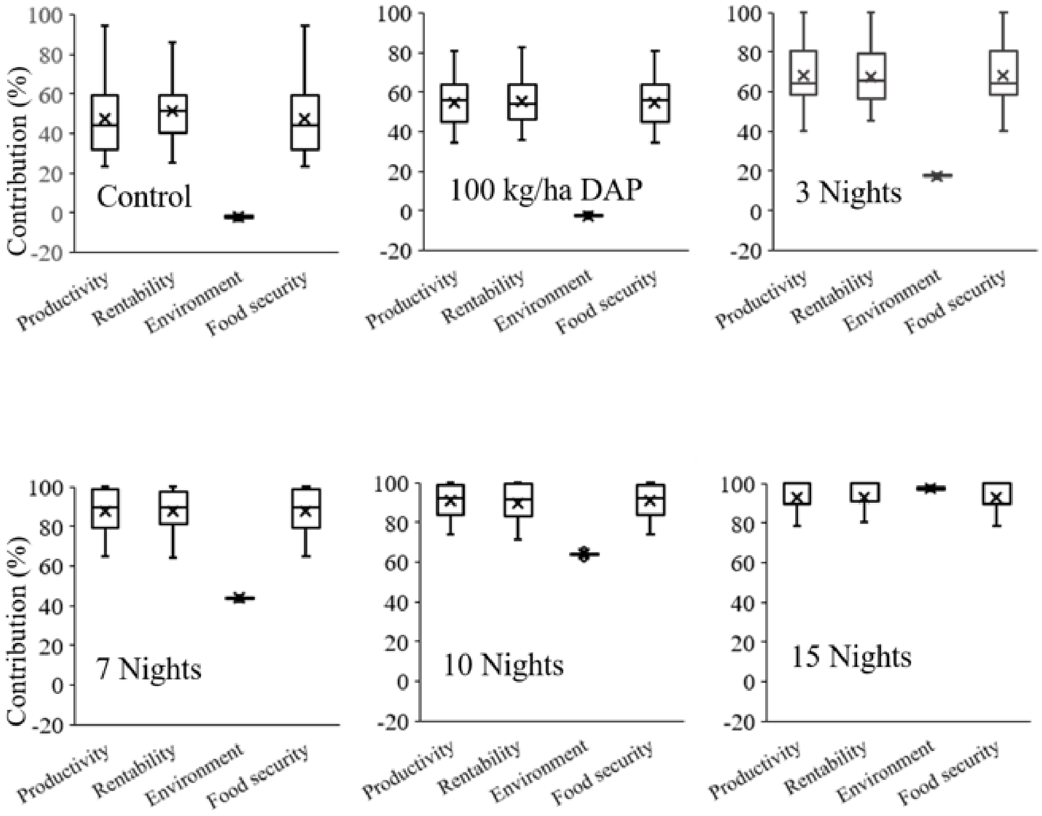

Figure 7

Contribution (%) of different soil fertility management strategies—Control, 100 kg/ha DAP, and 3-, 7-, 10-, and 15-night cattle corralling durations to four key performance indicators: Productivity, Profitability, Environmental Sustainability, and Food Security