FORAGE ESTABLISHMENT AND BIOMASS PRODUCTIVITY OF *Pennisetum purpureum* AND *Dolichos lablab* UNDER CONTRASTING RAINFED-WITH-IRRIGATION CONDITIONS IN SOUTHERN NIGER

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ABSTRACT

Seasonal feed shortages are still a major issue for livestock productivity in Sahelian agro-pastoral systems. This study compared two forage species, two planting densities and two levels of organic manure to determine which factor had the most impact on establishment and biomass productivity of *Cenchrus purpureus* (Schumach.) Morrone (formerly *Pennisetum purpureum*) and *Lablab purpureus* (L.) Sweet (formerly *Dolichos lablab*). The experiments were conducted during the 2023–2024 cropping season in two contrasting agro-ecological zones in southern Niger (Maradi and Konni) using a factorial randomized complete block design with three replications. Two forage species, planting densities of 10,000 and 20,000 hills ha^{-1}, and organic manure rates of 0 and 3 t ha^{-1} DM were used as treatments. The system was mainly rainfed and supplemental irrigation was done only during critical dry periods to avoid crop failure. At Maradi, *P. purpureum* produced up to 35.3 t DM ha^{-1} in the combination of a high planting density and manure application. The yields in Konni were below 14 t DM ha^{-1} in all treatments. *D. lablab* was established and performed well at both sites and remained consistent. Overall, differences in biomass production were mainly driven by forage species used and not density of plants or manure application. The results of this study make clear the importance of site-specific species selection in order to improve forage availability in Sahelian systems. Increasing the planting density or manure only works well when the soil is moist enough to have a good crop response.

Keywords: *Cenchrus purpureus; Lablab purpureus*; forage productivity; Sahel; Niger

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INTRODUCTION

Livestock in the semi-arid Sahelian region is at the heart of household food security, social identity and risk management in mixed crop-livestock communities such as those in Niger. However, this sector is under increasing pressure with seasonal feed shortages, diminishing pasture productivity and erratic rainfall from year to year. Substantial feed deficits and land-use change and demographic pressure have exacerbated in the past year in the dry season, with serious implications for livestock productivity and the resilience of agro-pastoral systems (Bayala et *al*., 2014; Amole et *al*., 2021; Karimou, 2022). Agricultural production of forage is of utmost importance for livestock productivity and agricultural stability in the Sahel, where decades of overgrazing have pushed the natural rangelands to their limits (Hiernaux et *al*., 2015). Cultivated forage resources for low-input, rainfed conditions can complement natural pastures and enhance feed supply (Amole et *al.*, 2021). In Niger, land tenure insecurity and a depleted natural resource base hamper the transition to better forage production systems (FAO, 2017). Of all cultivated forage species, *Pennisetum purpureum (Napier grass)* and *Dolichos lablab (lablab bean)* have received increased interest in light of their contrasting but not necessarily mutually exclusive agronomic and functional attributes in semi-arid conditions. *P. purpureum* (Napier grass) is known for its high biomass production potential and rapid vegetative regrowth ability, which makes it an ideal candidate for cut-and-carry feeding systems when soil humidity and fertility are good (Nyambati et *al*., 2010; Maleko et *al*., 2019). However, its establishment success and biomass productivity are highly influenced by the climatic environment, particularly in the Sahelian climate, which is characterised by high interannual variability and long dry seasons. *D. lablab*, a multi-purpose annual forage legume, is relatively adaptable to intermittent drought, and can be fed low input quantities and in a way is able to produce protein-rich biomass and contribute to soil fertility by biologically fixing nitrogen (Ndikumana & de

Leeuw, 1996a, b; Maass et *al*., 2010). As well as synthesis results and socio-technical studies in southern Niger, the agroecological relevance of *D. lablab* and farmers' acceptance of the plant has been recognised, while the adoption of *P. purpureum* is still very limited (Aziz et *al*., 2026a, b). The potential of integrating forage legumes and perennial grasses into agro-pastoral systems is well known, but successful integration must be based on a prior understanding of the establishment and biomass productivity of each species when grown in the context of local conditions and simple management. In semi-arid areas like Niger, planting density and organic nutrient inputs are among the most important potential ways of influencing forage establishment and yield in the environment where soils are usually poor in organic matter and rainfall is intermittent, leading to strong spatial differences of crop performance even in the shortest distances (Bayala *et al*., 2014). In general, there are few case studies of establishment and biomass performance of *P. purpureum* and *D. lablab* in dry Sahelian agro-ecological conditions in Niger. This study therefore investigated how forage species, planting density, and organic manure application jointly influence establishment, dry matter yield, and regrowth performance at two contrasting sites in southern Niger.

MATERIALS AND METHODS

Nomenclatural note: *Pennisetum purpureum* (Napier grass) and *Dolichos lablab* (lablab bean) have been classified as *Cenchrus purpureus* (Schumach.) Morrone and *Lablab purpureus* (L.) Sweet, respectively. The same genus names are retained throughout this paper to follow the authors' previous work on these forage species in Niger. This also ensures continuity with the regional agronomic literature and smallholder farming extensions, where the earlier naming is still used.

Study sites and environmental conditions: The field experiment was conducted in the 2023-2024 cropping season at two sites (Maradi and Konni) to capture the main agro-ecological gradient of southern Niger (Fig. 1). These are the major agro-pastoral production systems of the country, spanning a rainfall and soil continuum from the Sahelo-Sudanian zone to the drier Sahelian zone. The Maradi site is located in the Sahelo-Sudanian zone (13°30′ N, 7°06′ E) and is characterized by a semi-arid climate with a unimodal rainfall pattern concentrated between June and September. The average annual rainfall is 400 to 600 mm with high interannual variability. The soils are primarily tropical ferruginous soils (Lixisols), moderately deep and leached, with low organic matter and weak structural stability. These soils are consistent with the Lixisol classification (IUSS WRB, 2022; Lee et *al*., 2023) based on their argic horizon, moderate base saturation, and a weakly alkaline reaction (pH 7.5). The soil analysis revealed a pH of 7.5 at both sites. Although there is some literature which suggests that these crops prefer acidic soils (Ferralsols), this neutral to slightly alkaline condition is accurate for the southern Niger region. Such a context is a good starting point for how these forages respond to a local environment but not idealized and is of fundamental importance for the availability of nutrients and microbial activities during the growing process. The site of Konni in the Tahoua region (13°47′ N, 5°15′ E) is in the Sahelian region and the average annual rainfall is rarely above 350 mm. The long dry season (8 to 9 months) characterizes the region, accompanied by high evapotranspiration rates and shallow Arenosols and Regosols with coarse sandy textures and low water-holding capacity. The soils are very low in organic matter even with some local variation and are very weak structurally. The coarse sand (68%) and weak soil structure are strongly in accordance with the Arenosol classification (IUSS WRB, 2022; Lee et *al.*, 2023) of the sandy Sahelian landscape in the Tahoua region, and not lithosols which are skeletal soils over hard rock. The Konni site illustrates the severe climatic and edaphic conditions of pastoral landscapes in the western Sahel.

Crop husbandry: In the experimental period, cumulative rainfall was 559.3 mm (2023) and 570 mm (2024) in Maradi, compared with 456 mm (2023) and 462 mm (2024) in Konni. The crop life was mainly controlled by seasonal rainfall, but supplemental irrigation was used during periods of prolonged drought to prevent crop loss and to keep plants alive. This irrigation was not intended to replace rainfall but to avoid crop failure during critical moisture-stress periods. Hence, the production system was rainfed forage production supported by strategic supplemental irrigation. Supplemental irrigation was applied sparingly during prolonged dry spells (rainfall deficit exceeding 10 days), delivering approximately 20–40 mm per event through gravity-fed systems from nearby boreholes. This approach helped maintain plant viability while preserving the predominantly rainfed character of the forage systems.

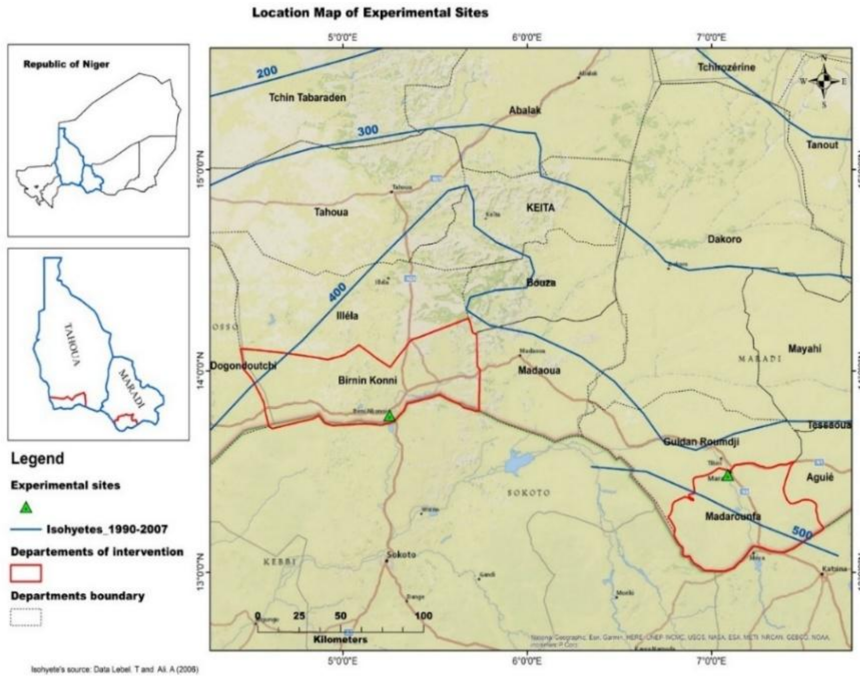

Figure 1: Geographical location of the two contrasting study sites — Maradi (Sahelo-Sudanian zone) and Konni (Sahelian zone) — illustrating the agro-ecological gradient covered by this study in southern Niger

Experimental design and treatments: The experiment was conducted using a factorial randomized complete block design (RCBD) at each site, with three replications in order to account for spatial variation. Three factors were considered in factorial design, and eight different treatment combinations were identified:

- Forage species: *P. purpureum* and *D. lablab*.
- Planting density: 10,000 and 20,000 hills ha^{-1}.
- Organic fertilization: 0 and 3 t ha^{-1} (dry matter basis) of well-decomposed manure from farmyard.

The manure was a stabilized mix of bovine and small ruminant with an estimated total nitrogen content of 1.2 to 1.5%. This is consistent with the estimate of partially mineralised organic matter in the Sahelian zone (Bationo et *al*., 2007; Ayantunde et *al*., 2018). Each plot was 20 m² (5 m × 4 m) with enough space between plots and blocks to minimize border effects and to allow for access to light and soil resources.

Crop establishment and management: Both species were established using the method that worked best for their growth habits: *D. lablab* was planted using certified seeds at a depth of 3-5 cm. *P. purpureum* was propagated by three-node stem cuttings. The cuttings were planted obliquely, with two nodes buried to provide good anchorage and one seed planted aboveground for bud emergence. Any hills that failed to develop were replanted within the first three weeks. Farmyard manure was added to the top 15 cm of the soil two weeks before planting in order to ensure fertilization at crop stage and minimize surface loss. As in local small-scale farming operations, no mineral fertilizers were used. The plots were kept weed-free through manual hoeing throughout the growing cycle to avoid competition for resources. A minimal supplemental irrigation was applied to seedling and stump survival during critical dry spells to help the plants survive. The water supply was only for preventing crop failure and maintaining plant viability during extreme moisture stress. This did not alter the fundamentally rainfed nature of the experimental cycle, which relied solely on natural Sahelian rainfall.

Data collection and dry matter determination: Biologically, aboveground biomass (stems and leaves) were harvested manually from the internal sampling area of each plot using a random process to avoid any border effects. Fresh biomass was weighed in the field using a calibrated digital scale (± 10 g accuracy). For dry matter (DM) determination, a representative subsample of ~500 g was collected from each harvested plot. Subsamples were placed in labelled paper bags and taken to the laboratory for analysis. From the laboratory, the samples were weighed to obtain fresh subsample weight and then oven-dried for about 48-72 hours at 65°C to be constant weight in a forced air-drying oven. Samples were reweighed after drying and a constant weight was observed if the two measurements differed by less than 1%. Dry matter content (%) was calculated using the following formula:

$$DM(\%) = \frac{Dry\ weight}{Fresh\ weight} \times 100$$

The total dry matter yield per plot was then computed as:

$$DM\ yield\ (kg) = Fresh\ biomass\ (kg) \times \frac{DM\ (\%)}{100}$$

Dry matter yield was subsequently extrapolated to hectare on (t DM ha^{-1}) basis to the harvested area. This direct oven drying method can accurately estimate the dry matter content of biomass and ensure reliable comparison of species, treatments and sites in the field.

Estimation of livestock carrying capacity: To assess the practical relevance of forage production, theoretical livestock carrying capacity was estimated for the best-performing treatment, based on a daily dry matter requirement of 1.0 kg per small ruminant and an assumed utilization rate of 70%, consistent with cut-and-carry feeding systems in the Sahel (Richard et al., 1990). Applied to the best-performing treatment (Maradi, high density with manure; 35.3 t DM ha^{-1}), this corresponds to an estimated carrying capacity of approximately 68 small ruminants ha^{-1} yr^{-1}.

Statistical analysis: Data were reported in Microsoft Excel (version 2021) and analysed using IBM SPSS Statistics version 26. Since the two sites were significantly different in rainfall and soil, analyses were conducted separately for each site. For the first harvest, a three-way ANOVA was performed with forage species, planting density and organic manure amendment as fixed factors. For the subsequent regrowth cycle of *P. purpureum*, a two-way ANOVA was performed to test the effects of planting density, manure amendment and their interaction. *D. lablab* was not included in regrowth analysis since it has been only harvested once. Prior to ANOVA, the normality of residuals and homogeneity of variances were checked with Shapiro-Wilk and Levene's tests ($p > 0.05$). If data were not consistent with normality ($p < 0.05$ in Shapiro-Wilk) then appropriate transformations were applied - $\log_{10}$-transformation for heteroscedastic distributions (in particular the cumulative biomass yield is log-normal) and square root transformation for count and percentage data (establishment rates, tiller number, leaf number). All transformed data were then back-transformed and the 95% confidence intervals were calculated and reported in the main results tables. The mean and 95% confidence intervals were then separated by Tukey's honest significant difference test at a 5% significance level. Pearson correlation analysis was also performed to find the relationship between vegetative growth parameters and dry matter yield.

RESULTS

Environmental conditions and physicochemical properties of soils: The physicochemical analysis of the topsoil at both sites under investigation confirmed the strong constraints of Sahelian agro-ecosystems (Table 1). Both locations are slightly alkaline (pH 7.5-7.7) and very low in electrical conductivity, indicating non-saline conditions. Although phosphorus levels are relatively moderate (19.7-23.6 mg/kg), the organic carbon and total nitrogen content are still critical in the soil; in Maradi, they are significantly lower, indicating a serious lack of soil organic matter and the need for organic manure. These edaphic differences, as well as the rainfall gradient, provided a strong basis to evaluate the adaptive capability of *P. purpureum* and *D. lablab.*

Table 1: Physicochemical properties of the topsoil (0–20 cm) at Maradi and Konni experimental sites.

Soil Parameters (Units)	Maradi (Mean ± SD)	Konni (Mean ± SD)
pH (H_2O)	7.5 ± 0.15	7.7 ± 0.12
Electrical Conductivity (µS/cm)	80.8 ± 6.40	74.4 ± 5.20
Available Phosphorus (mg/kg)	19.7 ± 2.10	23.6 ± 1.85
Organic Carbon (mg/kg)*	141.6 ± 12.4	223.2 ± 15.6
Total Nitrogen (mg/kg)*	106.7 ± 9.50	127.6 ± 11.2
Particle size distribution		
Clay (%)	10.0 ± 1.20	8.0 ± 0.85
Silt (%)	31.0 ± 2.45	24.0 ± 1.90
Sand (%)	59.0 ± 4.15	68.0 ± 3.75

Note: SD = Standard deviation; n = 3 soil samples per site. pH determined in water (1:2.5 soil:water ratio); EC = Electrical conductivity; P = Available phosphorus (Bray-1 method); OC = Organic carbon; TN = Total nitrogen.

Establishment and survival of forage species: Establishment rates were reported to be very varied for different treatments (Table 2). The establishment of seedlings was better over manure amendments, especially at the Maradi site. At Konni, *P. purpureum* establishment was poor and erratic and ranged from 39.0 ± 24.0% to 50.5 ± 25.3%, with no correlation with organic fertilization. Planting density also had a negative effect on establishment, which was worse for coarse soils under water-limited conditions. Conversely, *D. lablab* was more established and homogeneous in Konni at 72.0 ± 15.6% to 85.0 ± 14.1% across all the treatments. Both species did better at Maradi, where *P. purpureum* established from 70.0 ± 15.6% to 82.3 ± 12.1% and *D. lablab* was fully established (100%) regardless of treatment. *D. lablab* is plastic in all environments, and *P. purpureum* is very sensitive to the local pedoclimatic situation.

Table 2: Influence of site, planting density, and organic amendment on the establishment rate (%) of P. purpureum and *D. lablab*.

Site	Species	Planting Density (D)[1]	Amendment (A)[2]	Establishment Rate (%)
Konni	*P. purpureum*	LD	WM	47.5 ± 17.7
		LD	WthM	47.5 ± 25.3
		HD	WM	39.0 ± 24.0
		HD	WthM	50.5 ± 25.3
	D. lablab	LD	WM	81.3 ± 12.5
		LD	WthM	85.0 ± 14.1
		HD	WM	80.5 ± 16.6
		HD	WthM	72.0 ± 15.6
Maradi	*P. purpureum*	LD	WM	72.5 ± 17.7
		LD	WthM	75.0 ± 14.7
		HD	WM	70.0 ± 15.6
		HD	WthM	82.3 ± 12.1
	D. lablab	LD	WM	100.0 ± 0.0
		LD	WthM	100.0 ± 0.0
		HD	WM	100.0 ± 0.0
		HD	WthM	100.0 ± 0.0

Notes: Values are mean ± standard deviation (n = 3 replicates per treatment at each site). LD = Low planting density (10,000 hills ha^{-1}), HD = High planting density (20,000 hills ha^{-1}), WM = With organic manure (3 t ha^{-1} DM); WthM = Without organic manure.

Vegetative growth dynamics of *P. purpureum:* The plant growth of *P. purpureum* was very different in the experimental treatments and regrowth cycle (Table 3). In the first regrowth stage, the minimum plant height (67.2 ± 34.1 cm) was observed in low-density unamended (LD WthM) conditions, whereas the maximum (81.5 ± 40.1 cm) occurred in high-density manured (HD WM) plots. The planting density is directly related to the vertical elongation of the hill, and this was also the case in the latter case when organic amendments were applied. The tiller number per hill was between 40.2 and 48.2, and there was no difference between the two treatments. Leaf number per hill ranged from 127.5 to 151.5 in the first regrowth, slightly higher in manured treatments but not statistically significant. In the second regrowth cycle, the plant height decreased a bit in the two treatments, but tiller number and leaf number increased, which indicated compensatory growth after cutting. Two-way ANOVA indicated that planting density and manure application had a very strong impact on plant height in both regrowth cycles, whereas tiller number and leaf number were not significantly impacted by the two factors (Table 4).

Table 3. The plant growth rates of *P. purpureum* in Maradi plant densities and organic manure treatment.

Treatment (Density × Manure)	Plant height T1 (cm)	Plant height T2 (cm)	Tiller number T1	Tiller number T2	Leaf number T1	Leaf number T2
LD WthM	67.19 ± 34.10 b	48.86 ± 21.85 b	42.72 ± 33.57 a	52.61 ± 30.36 a	135.17 ± 100.71 a	259.81 ± 203.10 a
LD WM	71.31 ± 25.29 b	58.56 ± 29.50 ab	48.17 ± 29.14 a	51.06 ± 28.73 a	151.50 ± 87.43 a	241.97 ± 193.24 a
HD WthM	73.21 ± 34.60 ab	57.50 ± 30.35 ab	40.17 ± 32.06 a	48.57 ± 34.39 a	127.50 ± 96.19 a	262.33 ± 232.40 a

HD WM	81.54 ± 40.11 a	58.22 ± 28.43 a	47.28 ± 37.35 a	54.93 ± 43.43 a	148.64 ± 112.30 a	245.88 ± 226.52 a

Note: Values are mean ± SD (n = 3 replicates per treatment). LD = Low planting density (10,000 hills ha^{-1}); HD = High planting density (20,000 hills ha^{-1}); WM = With organic manure (3 t ha^{-1} DM); WthM = Without organic manure; T1 = First regrowth cycle; T2 = Second regrowth cycle. Within each column, means followed by different lowercase letters are significantly different (Tukey HSD, α = 0.05). NS = not significant.

The two-way ANOVA for the effects of planting density and organic manure application on vegetative growth parameters are shown in Table 4.

Table 4: Effects of planting density and organic manure application on vegetative growth parameters (Two-way ANOVA) during the first (T1) and second (T2) regrowth periods.

Source of variation	Plant height T1	Plant height T2	Tiller number T1	Tiller number T2	Leaf number T1	Leaf number T2
Density (D)	<0.001***	<0.001***	0.920 (NS)	0.250 (NS)	0.980 (NS)	0.210 (NS)
Fertilization (A)	0.250 (NS)	<0.001***	0.850 (NS)	0.830 (NS)	0.740 (NS)	0.790 (NS)
Interaction (D × A)	0.005**	<0.001***	0.860 (NS)	0.450 (NS)	0.870 (NS)	0.980 (NS)

Note: D is planting density; A is organic manure amendment; D × A is interaction between density & manure. T1 = First regrowth cycle T2 = Second regrowth cycle. * $p < 0.05$; ** $p \leq 0.01$; *** $p \leq 0.001$: NS = not significant.

Legend: Two-way ANOVA for each parameter and regrowth period. *$p \leq 0.05$; **$p \leq 0.01$; ***$p \leq 0.001$: NS = not significant. T1 = first regrowth; T2 = second regrowth.

Combined effects of species and management on first-harvest biomass: At the first harvest, the three-way ANOVA found that forage species was the main factor affecting dry matter production at both sites, while planting density, organic amendment, and all interaction terms were not statistically significant. For the Konni site, the three-way ANOVA (Table 5) indicated that forage species was highly significant (F = 14.94, p = 0.001), whereas planting density (p = 0.566), organic amendment (p = 0.327), and all interaction terms were not statistically significant. This indicates that at the water-limited Konni site, species choice is the main determinant of forage productivity, independent of management intensification through increased planting density or organic input. At the Maradi site, species was also the only statistically significant factor (F = 13.69, p = 0.002). Planting density (p = 0.141), organic amendment (p = 0.194), and all interaction terms were not statistically significant. Despite the more favorable environmental conditions at Maradi, management factors did not significantly increase yields beyond the species-specific potential. This pattern indicated that forage species selection, not management intensity, determines the productivity ceiling at each site. Taken together, the first-harvest data at both sites consistently identified species as the dominant significant factor, while density and manure remained non-significant within each site-level model. Because the two sites were analysed separately, this pattern should be read as a within-site result rather than a formally tested site × species effect; it nonetheless suggests that species choice deserves particular attention when designing sustainable forage systems.

Table 5: Three-way ANOVA summary for dry matter yield (1st cut, 2024) at Konni and Maradi sites.

Source of Variation	**df**	***F*-value (Konni)**	***p*-value (Konni)**	***F*-value (Maradi)**	***p*-value (Maradi)**
Species (S)	1	14.940	0.001	13.688	0.002
Density (D)	1	0.344	0.566	2.402	0.141
Amendment (A)	1	1.022	0.327	1.837	0.194
S × D	1	0.060	0.810	0.101	0.754
S × A	1	1.557	0.230	0.060	0.810
D × A	1	0.498	0.491	0.559	0.465
S × D × A	1	0.178	0.679	0.234	0.635
Note: Significant p-values (p ≤ 0.05) are indicated in bold. NS = Not Significant.					

Note: Significant p-values ($p \leq 0.05$) are indicated in bold. NS = Not Significant. df = Degrees of freedom; S = Species; D = Planting density; A = Organic manure amendment. Interactions: S × D, S × A, D × A, S × D × A. Significant p-values ($p \leq 0.05$) are shown in bold. NS = Not significant.

At the initial harvest, variations in biomass yield across sites and treatments combinations were substantial and agronomically significant (Fig. 2). At the Maradi site, *D. lablab* consistently out-yielded *P. purpureum* in terms of primary biomass accumulation across most experimental units. Organic manure amendments tended to enhance dry matter yield, with the most pronounced effects observed under high-density planting. Conversely, overall biomass productivity at Konni was lower for both species compared to Maradi. Under the more arid conditions of the Konni site, the influence of planting density and fertilization on yield was less discernible. These first-harvest data show that local environmental conditions influenced early biomass accumulation at least as strongly as management practices did, under the irrigation-supported rainfed system used here. Figure 2 illustrates this clearly: Maradi already outperformed Konni in biomass productivity from the very first cutting. Dry matter yield (t DM ha⁻¹) of P. purpureum and D. lablab as a function of planting density and organic manure application at two pedoclimatically contrasting sites in Niger (Maradi and Konni).

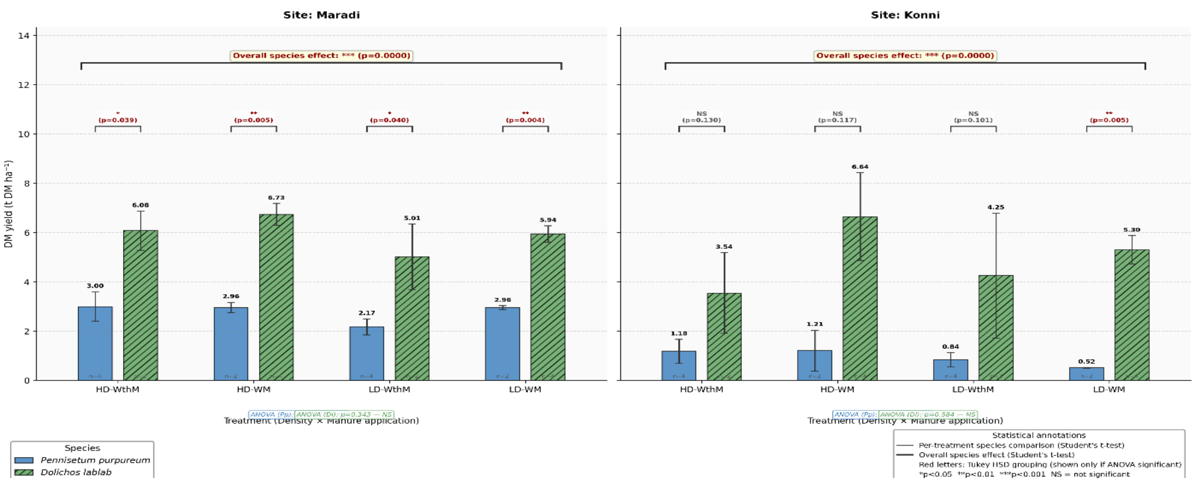

Figure 2: Dry matter yield at first harvest depending on species, site, and management practice. Legend: HD = High Density (20,000 hills ha⁻¹); LD = Low Density (10,000 hills ha⁻¹); WM = With Manure (3 t ha⁻¹ of well-decomposed farmyard manure); WthM = Without Manure. Error bars represent the standard error of the mean (SEM, n = 3). Small brackets: per-treatment species comparison (Student's t-test). Large bracket: overall species effect. NS = not significant; *p ≤ 0.05; **p ≤ 0.01; ***p ≤ 0.001.

Cumulative aboveground biomass production of *P. purpureum*: The cumulative dry matter yield of *P. purpureum* varied markedly between sites (Table 6). At Maradi site, yield ranged from 15.6 ± 3.4 t DM ha⁻¹ under low planting density without manure to 35.3 ± 5.1 t DM ha⁻¹ under high planting density with manure. In the same site, the planting density significantly influenced cumulative biomass, where manure effects were not significant within the same density level. In Konni, neither planting density nor manure significantly affected cumulative yield with biomass ranging from 10.7 ± 3.4 to 13.7 ± 5.4 t DM ha⁻¹.

Table 6: Combined effect of planting density and organic manure application on the cumulative dry matter yield (t DM ha⁻¹) of *P. purpureum* at Maradi and Konni sites.

Site	Density[1]	Manure[2]	Mean ± SD (t DM ha⁻¹)	95% CI
Maradi	LD	WthM	15.58 ± 3.44b	10.4–20.8
Maradi	LD	WM	15.52 ± 1.87b	12.2–18.8
Maradi	HD	WthM	27.41 ± 7.86a	13.1–41.7
Maradi	HD	WM	35.33 ± 5.07a	29.8–40.9
Konni	LD	WthM	10.73 ± 3.39a	5.89–15.6
Konni	LD	WM	13.17 ± 4.58a	6.56–19.8
Konni	HD	WthM	13.73 ± 5.43a	6.03–21.4
Konni	HD	WM	12.76 ± 2.21a	9.97–15.6

Note: Values are mean ± SD (n = 3 replicates per treatment). LD = Low planting density (10,000 hills ha⁻¹); HD = High planting density (20,000 hills ha⁻¹); WM = With organic manure (3 t ha⁻¹ DM); WthM = Without organic manure. CI = Confidence interval. Within a column, means followed by different superscript letters differ significantly (Tukey HSD, α = 0.05).

Pairwise comparisons of treatment effects on cumulative biomass yield are summarized in Table 7. Post-hoc comparisons revealed contrasting treatment effects between the two sites. At Maradi, planting density exerted a significant influence on the measured parameters ($p \leq 0.05$), whereas the effect of organic manure remained non-significant within the same density levels. Conversely, at the Konni site, no significant differences were observed across any treatment combinations (p>0.15), indicating that environmental constraints likely superseded management effects.

Table 7: Pairwise comparison of treatment effects on cumulative biomass yield of *P. purpureum* at Maradi and Konni sites.

Site	Comparison	*p*-value
Maradi	LD WthM vs LD WM	0.988
	LD WthM vs HD WthM	0.021 *
	LD WthM vs HD WM	0.001 **
	LD WM vs HD WthM	0.021 *
	LD WM vs HD WM	0.001 **
	HD WthM vs HD WM	0.092
Konni	All Comparisons	> 0.15 (ns)

Note: LD = Low planting density (10,000 hills ha^{-1}); HD = High planting density (20,000 hills ha^{-1}); WM = With organic manure (3 t ha^{-1} DM); WthM = Without organic manure. * $p \leq 0.05$; ** $p \leq 0.01$; ns = Not significant ($p > 0.05$). Significance levels: * $p \leq 0.05$; ** $p \leq 0.01$; ns = not significant.

Temporal biomass dynamics and pedoclimatic drivers: *P. purpureum* biomass accumulation exhibited distinct temporal patterns driven by rainfall seasonality, soil physical properties, and site-specific conditions (Fig. 3). At Maradi, six harvest cycles were achieved, with peak productivity occurring during the fifth cutting (mid-July 2024), coinciding with maximum rainfall. Conversely, Konni supported only three cycles, characterized by slower regrowth and significantly lower cumulative yields. These contrasting dynamics were primarily dictated by water availability rather than chemical fertility. Although Konni exhibited higher soil organic carbon and total nitrogen (Table 1), its coarser texture (68% sand) limited water-holding capacity. In contrast, the finer-textured soils at Maradi (31% silt) facilitated superior moisture retention. Combined with higher annual precipitation (approx. 570 mm vs. 462 mm), these favorable hydrological conditions allowed Maradi to consistently outyield Konni.

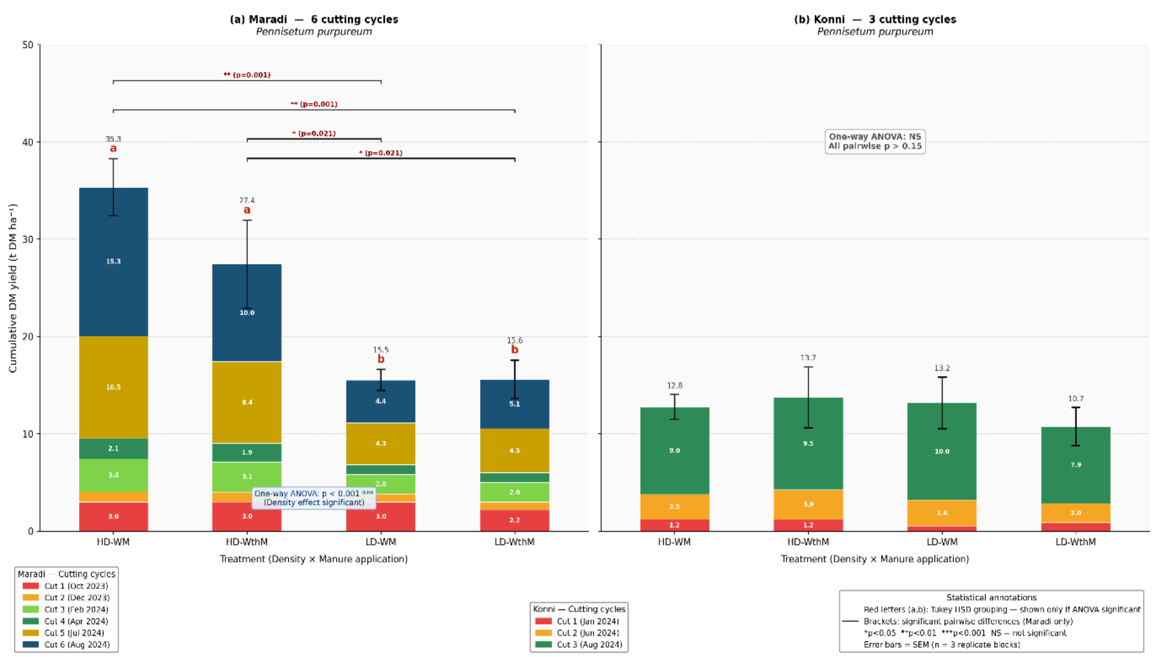

Figure 3: Rainfall-driven biomass accumulation dynamic of *P. purpureum*. (a) Maradi: six cutting cycles (October 2023 – August 2024); (b) Konni: three cutting cycles (January – August 2024); HD = High Density (20,000 hills ha^{-1}); LD = Low Density (10,000 hills ha^{-1}); WM = With Manure (3 t ha^{-1}); WthM = Without Manure. *Error bars = Standard error of the mean (SEM, n = 3 replicates). Coloured segments represent contribution of each individual cutting cycle to cumulative DM yield. Letters (a, b) indicate significant differences between treatments (Tukey HSD, α = 0.05) at Maradi site. NS = Not significant (Konni). DM = Dry matter. Coloured segments represent the contribution of each individual cutting cycle to cumulative dry matter yield. Error bars represent the standard error of the mean (SEM, n = 3 replicate blocks). At Maradi site, means sharing the same letter are not significantly different (Tukey's HSD test, α = 0.05). NS = not significant (Konni).*

DISCUSSION

Results show that the forage productivity in the two study sites was determined by species performance and soil-water conditions as well as forage quality. At first harvest, species was the only factor that was important for dry matter yield in Maradi and Konni, while density of plants and organic manure amendment had limited impact. This means that selecting a forage species that fits the local environment is more important in this experiment in addition to management intensity. *D. lablab* exhibited greater ecological plasticity than *P. purpureum*. It achieved full establishment at Maradi and relatively stable rates at Konni (72–85 %), likely owing to its substantial seed reserves and robust taproot system. In contrast, *P. purpureum* proved highly sensitive to initial water stress at the Konni site. As a large-seeded legume, *D. lablab* possesses substantial seed reserves and a robust initial taproot system (Cook *et al*., 2020) that allows for immediate access to soil moisture and rapid growth at early stages (Ndikumana & de Leeuw, 1996a, b; Maass *et al*., 2010). But the erratic and suboptimal establishment of *P. purpureum* at Konni (39.0-50.5%) indicates a high-water sensitivity (Nyambati *et al.*, 2010; Maleko *et al*., 2019). Since *P. purpureum* uses so many resources into early root establishment, it increases aboveground biomass gradually and does not achieve its full productivity in subsequent regrowth cycles. This establishment difficulty is a major bottleneck to using the species in more arid areas. The lower productivity at Konni seems to be more a result of water limitation than soil nutrient status. While Konni had slightly more organic carbon and total nitrogen than Maradi, its sandy soil texture in particular probably reduced the water holding capacity and fast drying between rainfall events. This may explain the weak response to manure and planting density at this site. In these conditions, nutrient addition alone is unlikely to increase biomass production unless soil moisture constraints are also addressed (Stroosnijder, 2009; Blum, 2017; Amole et *al.*, 2021). The drying of the upper soil layers for this crop was so fast that root growth and nutrient uptake would have been impaired. At Maradi, the finer soil texture (31% silt) enhanced topsoil moisture retention, providing the hydrological buffer to keep young seedlings from desiccation and to promote vegetative regrowth into the dry periods between rainfalls. Under favourable moisture conditions, owing to Maradi's finer soil texture and supplemental irrigation, the overall DMY reached a maximum of 35.3 ± 5.1 t DM ha^{-1}, reflecting the combined benefit of management and resource availability. The significant increase in density ($p \leq 0.05$), but not manure ($p > 0.05$) of the plants at a given density, indicates that canopy structure and light capture were the main factors driving up the cumulative biomass. The intense competition for light in large stands led to vertical elongation (Maleko *et al.*, 2019) and plants tend to extend their stems to have the best chance to get light captured. This trend was even more pronounced in the denser, manured plots where organic amendments provided nitrogen and phosphorus to sustain rapid cell division. Management intensification only pays off when the resources (water and nutrients) are sufficient to support the increased metabolic demand (Payne, 2000). Although there were significant differences in plant height and total biomass in the first regrowth phase, tiller and leaf numbers were similar across all treatments. This indicates a conservative morphological strategy that emphasizes apical dominance. Rather than building up individual phytomers (tillering), *P. purpureum* prefers to grow existing tillers. This compensatory growth strategy allows the plant to restore its photosynthetic canopy quickly after harvest without the high energy cost of growing new axillary buds in a soil with moderate fertility (Kropff & van Laar, 1993). However, a clear change in morphology occurred in the second regrowth cycle (the plant height and tiller and leaf numbers were slightly lower, with a significant increase in tiller number) which is typical of size-density compensation due to repeated defoliation. Cutting activated dormant basal buds in the stand for optimal ground cover production. In addition to water-use efficiency as the plants are less prone to surface evaporation and more likely to survive over several harvest cycles. The significant ANOVA relationship between density and manure shows that, while density determines the form of the vertical canopy structure, organic interventions are necessary to retain the nutrient pool that is necessary to continue regrowth for the long term. The results show that cutting frequency is linked to the time when water is available. *P. purpureum* is able to achieve six cutting cycles at Maradi and only three at Konni. The highest productivity was achieved by the fifth cutting (July 2024) at Maradi for the highest amount of precipitation (Blum, 2017) and this indicates that regrowth occurs when defoliation is optimal for the soil moisture (Blum, 2017). The *P. purpureum* production was enhanced using supplemental irrigation at Maradi by four to five times with 68 small ruminants ha^{-1} yr^{-1} compared to natural rangelands (10-15 small ruminants ha^{-1} yr^{-1}). Note that the above results were obtained when a predominantly rainfed system with minimal supplemental irrigation was used during dry spells, but still 2 to 3 times higher than in natural rangelands at low density without intervention, the closest to unmanaged conditions observed in this study, and that this is the pathway on which Niger's feed gap can be filled. Collectively, these results suggest the need for an agro-pastoral forage development strategy that is specific to each site in the Sahel. In dry and sandy areas such as Konni, D. lablab should be the most reliable choice for establishment in the absence of water, while productivity of P. purpureum is likely to be dependent on water harvesting or supplementary irrigation. In relatively favourable locations such as Maradi, high planting density is likely to increase the biomass production of P. purpureum in places with sufficient moisture to support regrowth.

Conclusion: The establishment and biomass productivity of crops had a very different pattern of species and locations in southern Niger. *D. lablab* established more reliably across both sites, whereas *P. purpureum* reached its full biomass potential (35.3 t DM ha^{-1}) only under the more favourable soil moisture conditions of Maradi. In Konni, higher planting density and organic manure did not significantly improve yield. This indicates that water availability, rather than soil fertility, was the main limiting factor at this site. Choosing forage species suited to local conditions therefore appears to be an important lever for improving forage productivity in Sahelian systems, to be combined with appropriate water and soil fertility management; testing whether this factor outweighs management intensity across sites would require a combined analysis with site included as a formal factor. Future work should cover many growing seasons, more accurately characterize irrigation inputs and assess forage quality and animal performance in the field.

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