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Full Length Research Paper

Cowpea Varietal Performance in the Optimized Shrub (*P. reticulatum*) Intercropping System in Senegal

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Abstract

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The Sahel is a vulnerable semi-arid ecosystem for crop production due to climate change, recurring drought, desertification, and sandy soils with naturally low quality. Growing populations have increased cropping intensity and a loss of fallowing that has resulted in degraded soils. Agroecological management systems are needed that use local resources. A solution is the Optimized Shrub-intercropping System (OSS) that utilizes *Piliostigma reticulatum* at elevated densities (1200-1500 ha^{-1}) and produces significant amounts of annually coppiced biomass that is returned to soils. Research has shown OSS remediates soils, promotes crop drought resistance, and dramatically increases yields. However, there is no information on whether there are differential crop varietal responses to OSS, including low-input cowpea (*Vigna unguiculata* L. Walpers) which is an important protein food source. Therefore, the objective was to determine the effect of OSS on the growth and yield of diverse cowpea cultivars. The study was done at the Keur Ndary Ndiaye long-term experiment in Senegal that had a randomized complete block 2 X 4 factorial design (3 replications) with these treatments: 2 management systems (+OSS and -OSS) and 4 cowpea cultivars (B21, Mouride, Sam and Yacine). The study was done over 2 growing seasons that included plant growth measurements. Averaging across cowpea varieties showed that +OSS significantly increased seed yields from 658 to 1433 kg ha^{-1} in 2021 and from 107 to 868 kg ha^{-1} in 2022. In the presence of shrubs, the best varietal yielding performance in 2021 was Yacine (2007 kg ha^{-1}) and Mouride (1634 kg ha^{-1}); and in 2022 Sam (1113 kg ha^{-1}) and Yacine (975 kg ha^{-1}). Yacine had high yields both years and could be due it being a short duration variety. OSS with *P. reticulatum* increases crop yields and is a sustainable practice that utilizes a local resource that is very appropriate for subsistence farmers of Senegal.

Keywords: Shrub intercropping, *Piliostigma reticulatum*, cowpea, soil fertility.

Running Title: Optimized Shrub Intercropping with Cowpea.

1.0 INTRODUCTION

Cowpea, *Vigna unguiculata* L. Walpers is one of the major large-seeded legumes produced in the world, especially in West Africa (Boukar et *al*., 2018). It accounts for 85% of the dry legume area and 10% of the cropland for this region (Alène et *al*., 2012; Egbadzor et *al.,* 2014; FAOSTAT, 2017).

Senegal is the fifth largest producer of cowpea in West Africa, (FAOSTAT, 2016). It is important for subsistence farming households because it provides: an excellent food

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source (23-32% grain protein, 50-60% carbohydrate, and about 1% fat on a dry basis) (Jayathilake et *al.,* 2018), fodder for livestock (Cissé and Hall, 2003) and cash income (Dabat et *al*., 2012). Cowpea as a legume fixes atmospheric N_2, adding 50 to 115 kg N ha^{-1} to soil that can be used by subsequent crops (Bado, 2002). Thus, besides being a food source, it provides agronomic and sustainable services to rural agricultural households throughout West Africa.

However, cowpea yields in Senegal, are low, ranging from 200 to 500 kg ha^{-1} in 2016 to 2020 (ANSD, 2020), compared to the potential yields of improved varieties in research plots (1,500 to 3,300 kg ha^{-1}) (Krasova, 2003; Cissé, 2015). A major reason for the reduced yields is soil degradation due to the dramatic increase in rural populations that has increased cropping intensity. In turn this has caused a loss of fallowing, increased removal of crop residues after harvest, and stripping of the landscape for fuelwood all of which has significantly reduced organic inputs to soils and resulted in soil degradation (Diallo et *al*., 2019).

An agroforestry system that holds potential to address the agro-ecological challenges of the Sahel is the Optimized Shrub-intercropping System (OSS). It utilizes the native shrubs *Piliostigma reticulatum* or *Guiera senegalensis* that are established at high densities (1200 to 1500 shrubs ha^{-1}) and unlike traditional management of burning coppiced shrub residue, this biomass is annually incorporated. *P. reticulatum* extends from Senegal in the west to Sudan in the east and the Democratic Republic of Congo in the south (Hernandez et *al*., 2015).

P. reticulatum increases plant availability and uptake of nutrients (Dossa et *al*., 2009, 2010; 2013) and promotes carbon (C) sequestration (Lufafa et *al.*, 2008; Yelemou et *al*., 2013). This species also enhances rhizosphere microbiology by increasing: microbial biomass, respiration, microbial diversity and beneficial (Debenport et *al*., 2015; Diedhiou *et al*., 2021: Mason et *al*., 2023).Furthermore, OSS improves crop water relations, including reduction of crop water stress due to remediation of degraded soils (Bright et al, 2017) and by performing hydraulic lift (HL) of deep sub-soil water (Kizito et *al.*, 2006, 2007, 2012) that “bioirrigates” adjacent crops (Bogie et *al*., 2018). Finally, OSS dramatically increases yields of pearl millet (*Pennisetum glaucum* (L.) R. Br.) and groundnut (*Arachis hypogaea* L.) (Geiger and Manu, 1993; Dossa et *al.*, 2013; Debenport et *al.*, 2015; Bright et *al*., 2017, 2021).

However, there is no information on the response of cowpea to OSS nor whether cultivar type is affected by OSS. Therefore, the objectives of this experiment were to determine whether OSS increases cowpea yields as shown for other crops and to compare the performance of older, improved varieties to Sam, a newer variety with greater seed size and yield.

2.0 MATERIALS AND METHODS

2.1 Experimental Site

This study was done at the long-term *Piliostigma reticulatum* intercropping experiment near Nioro, Senegal, West Africa, in the southern Peanut Basin (13º45’N, 15º47’ W), within the Northern Sudanian climatic region (Sarr et *al*., 2013). The elevation is 18 m above sea level with 0-2% slopes. The predominant shrub in this region is *P. reticulatum* or "nguiguis" in Wolof with densities ranging from 134 to 288 shrubs ha^{-1} (Lufafa et *al*., 2008).

The *P. reticulatum* belowground biomass is characterized by a dimorphic growth pattern with > 90% of the root biomass found in a spreading pattern within 20 to 50 cm of the soil surface. It is anchored by a thick, woody tap root that branches and provides access to ground water (Kizito et *al*., 2006). If left uncut, *P. reticulatum* can be found growing as a tree but maintains a shrub growth habit when coppiced regularly (Lufafa et *al*., 2008).

The soil is sandy (> 90% at the surface), has a 6.2 pH, and a loose consistency with very little horizon differentiation or clay. The FAO taxonomic classification is a fine-sandy, mixed Haplic Ferric Lixisol (Kizito et *al*., 2006). Air temperatures range from 20.0 to 35.7ºC and the mean annual precipitation of 750 mm mainly comes mostly between July and September.

2.2. **Experimental Design**

In 2003, a 0.5 ha field was selected to develop the long-term experiment that met the dual requirements of having established shrubs in place and having been managed under a yearly groundnut-millet rotation for at least 50 years until 2000, when it was fallowed for 3 years. A randomized complete block 2 X 4 factorial split-plot design (3 replications) was implemented with these treatments: 2 management systems (+ and - Optimized Shrub-intercropping System, OSS) as the main plot and 4 cultivars as the split plot planted in 2021 and 2022. The cowpea varieties provided by the cowpea breeding program of ISRA based in CNRA in Bambey were Bambey 21, Sam, Mouride and Yacine. Table 1 provides general plant characteristics of each variety.

The main plots were 48 X 4.5 m (3 m between blocks) varietal sub-plots of 4.5 m×1.5 m that had four (4) rows (50 cm) with plant-to-plant spacing of 25 cm to give 160,000 plants ha^{-1}. Three (3) seeds were added per hill and thinned two plants after emergence followed by manual weeding every 20 days.

The OSS treatments were established in the winter of 2003 where - OSS had all shrubs removed manually and the +OSS had *P. reticulatum* seedlings added to the existing shrubs to achieve a shrub density ranging from 888 to 1555 ha^{-1}.

2.3 Crop Management

Before each rainy season (May or June), the shrubs were coppiced, cut into 5 to 10-cm lengths, and the residue was spread evenly over the +OSS treatment. This stands in contrast to the current management of burning coppiced *P. reticulatum* biomass prior to planting (Dossa et *al*., 2013; Lahmar et *al*., 2012). Shallow pre-planting tillage and other farmer practices in the region were implemented (Dossa et *al*., 2013). Crop planting occurred each late June

Table 1: Physiological properties of cowpea varieties.

Variety	Plant habit	Seed Coat	Matrurity (days)	Bacterial canker	Aphids	Thrips
Sam	Erect	White	58	Resistant	Tolerant	Tolerant
Yacine	Erect	Brown	62	Resistant	Resistant	Sensitive
Mouride	Semi erect	White	54-61	Resistant	Sensitive	Sensitive
B21	Erect	White	57-60	Sensitive	Sensitive	Sensitive

with weeding by hand hoeing and with an animal-drawn shallow cultivator to a 5-cm depth. After millet grain harvesting, the remaining millet biomass was left on the soil surface, but groundnut residue as per farmer practices was removed and fed to livestock (Dossa et *al*., 2013). During the cropping season, shrubs were coppiced twice per growing season and residues returned to soil surface. Shrubs regrew during the dry season when there was no weeding of the plots. This same crop and soil management practices were maintained from 2004 to 2022 (Doss et al., 2013; Bright et al., 2017).

2.4 Plant Measurements

The five plant growth measurements that are sensitive to drought on cowpea are described below (Ahmadikhah et *al.,* 2016; Lehler and Hawkins, 2022).

Plant height was done on 16 randomly selected plants by measuring from the crown to the highest leaf on the main stem. Measurements were made every twenty (20) days. Collar diameter was measured using a caliper for each of the 16 randomly selected plants every twenty (20) days. Forty days after planting was the data reported in this investigation as this was the sampling date when varieties showed the most significant differences in plant growth measurements.

At maturity, cowpeas were harvested, the pods were dried in the sun for 21 days, then threshed, and weighed. The weight of 100 seeds (g) of each treatment was determined. The biomass of 16 plants per treatment was weighed immediately after collection to determine fresh weight followed by drying at 60 ºC for 3 days and weighed.

2.5 Statistical Analysis

Statistical analysis was done with GenStat software for a split-plot design data with cropping system as the main plot and cowpea variety as the split-plot. Descriptive statistics and correlation tests between variables were done with ViTSel software. Differences were considered significant at $P<0.05$, and Tukey's honest significant difference test was used to separate significant effects of the treatments.

3.0 RESULTS

Averaging across all varieties and both years, the cowpea growth response was: 4.9 vs 5.6 mm collar diameter, 144 vs. 259 plant height cm; 507 vs.1151 kg grain yield ha^{-1}; 18.5 vs 18.8 g 100 seed wt, and 1289 vs. 2154 kg dry biomass ha^{-1} for -OSS vs. +OSS, respectively (Table 2). The increase of +OSS over -OSS was: 56, 13, 44, 2, and 40 % for grain yield, collar diameter, plant height, 100 seed weight and dry biomass yield, respectively. Overall, the best performances were recorded in 2022. The results of ANOVA showed significant differences on all measured parameters except Variety type on plant height (Table 3). The interaction of year with management system was highly significant for collar diameter ($p<0.001$) and grain yield ($p<0.001$). The interaction of variety by year had a very highly significant effect on 100-seed weight ($p<0.001$) and plant height ($p<0.001$).

Correlations among various cowpea properties within a cropping system are shown in Table 4. Many of the correlations were negative or had a low correlation coefficient (r value). There was a significant correlation between plant height and collar diameter for the +OSS treatment (r= 0.68) (Table 4) but not under -OSS (r = 0.12). A strong correlation in +OSS (r = 0.62) and a medium correlation in -OSS (r = 0.55) was found between dry biomass yield and collar diameter. Very weak correlations were observed between grain yield and the rest of the parameters under both management systems. The results showed that grain yield for the +OSS is negatively and weakly correlated with dry biomass (r= -0.45). Grain yield was negatively correlated with collar diameter (r= -0.57) and height (r= -0.26) and positively and weakly correlated with 100-seed weight (r=0.24).

The results showed that for both years all varieties responded positively to +OSS. The percent increase among varieties due to +OSS over -OSS ranged from 593 to 983 (Table 5). In 2021, Yacine and Mouride had the

Table 2: Effect of management system on cowpea growth parameters and yield averaged across all varieties.

Variable	2021		2022		Average		Percent Increase
	+OSS	-OSS	+OSS	-OSS	+OSS	-OSS	+OSS/OSS
Grain Yield (kg ha^{-1})	1433a†	658c	868b	107d	1140	148	670
Collar Dia. (mm)	4.1c	4c	7.1a	5.8b	5.6	4.9	13
Plant Height (cm)	206b	145c	311a	143c	259	144	44
100 Seed Weight (g)	18.8a	18.7a	18.8a	18.0b	18.8	18.5	2
Biomass (kg ha^{-1})	1728b	907c	2579a	1670b	2154	1289	40

†Values among four columns across years and management system followed by the same lower-case letter are not significantly different at P<0.05.

Table 3: F values from analysis of variance for the years 2021 and 2022.

Sources of variation	Plant Height	Grain Yield	Biomass	Collar Dia.	100 Seed Wt
Variety	8.4 ^{NS}	94***	16**	24***	3159***
Year	13***	153***	26***	382***	2.3 ^{NS}
Management System	63***	1480***	30***	35***	6*
Variety X Year	15**	85***	31***	12*	26***
Variety X System	3.4 ^{NS}	70***	1.9^{NS}	0.70 ^{NS}	19***
Year X System	14***	86***	0.08^{NS}	22***	2.1 ^{NS}
Year X Variety X System	1.8 ^{NS}	17***	0.7 ^{NS}	1.8 ^{NS}	6**

**P<0.05*
****** *P<0.01*
*******: *P<0.001*
^{NS} *Not significant*

highest seed yields but in 2022 it was Sam and Yacine (Table 4).

4. DISCUSSION

Averaging across all varieties and years, the results showed a highly significant effect of +OSS over the traditional management system (-OSS) on cowpea height, collar diameter, and yield (Table 2). These results are consistent with Ba et al. (2014) who found that the incorporation 4 Mg ha^{-1} of *P. reticulatum* biomass increased collar diameter, plant height and leaf count in millet (*Pennisetum glaucum* L.).

The above plant growth responses carried through with yields over all varieties and years with a remarkable 670% average increase over -OSS. The yield response was significant for each variety due to +OSS (Table 5) and when averaging across varieties (Table 2). This yield response with cowpea to +OSS is consistent with Dossa et al. (2013) and Bright et al. (2017) who showed dramatic millet (*Pennisetum glaucum* L.) and groundnut (*Arachis hypogaea* L.) responses to +OSS at the long-term intercropping experiment with *P. reticulatum* in Senegal. Thiaw (2018) also showed that the amendment of soils with *P. reticulatum* above ground litter promoted millet growth.

Table 4: Correlation coefficients (r values) among crop growth and yield variables for the two management systems across sampling years 2021 and 2022.

		Plant Height	Grain Yield	Biomass	Collar Dia.	100 Seed Wt
Plant Height	**+OSS**	-				
	-OSS	-				
Grain Yield	**+OSS**	-0.26	-			
	-OSS	0.22	-			
Biomass	**+OSS**	0.16	-0.45	-		
	-OSS	-0.17	-0.35	-		
Collar Dia.	**+OSS**	0.68	-0.57	0.62	-	
	-OSS	0.12	-0.51	0.55	-	
100 Seed Wt	**+OSS**	-0.08	0.24	-0.29	-0.05	-
	-OSS	0.02	0.35	-0.15	-0.08	-

Table 5: Effect of cropping system on cowpea varietal yield in 2021 and 2022.

	2021		**+OSS**	**2022**		**+OSS**
Variety	**+OSS*** **	**-OSS**	**Increase**	**+OSS*** **	**-OSS**	**Increase**
	-------kg ha^{-1}--------		%	-------kg ha^{-1}--------		%
B21	1019b†	147d	593	650b	78c	733
Mouride	1634a	204d	701	736b	102c	622
Sam	1071b	163d	557	1113a	158c	604
Yacine	2007a	240d	736	975a	90c	983
Mean	1433	189	647	848	107	736

†Values within a column of a sampling year and management system followed by the same lower-case letter are not significantly different at P<0.05.
***Indicates a significant effect of management system at P<0.001.

Previous research provides evidence for how +OSS could promote cowpea growth. First is the higher quality soil that develops from Optimized Shrub-intercropping with *P reticulatum* as shown by dramatic increases in total C and N, (Dossa et *al*., 2010; Bright et *al*., 2017) and reduction in P fixation in soil (Dossa et al. 2008). Secondly, the *P. reticulatum*-OSS combination increases the availability and uptake of nutrients (Dossa et *al*., 2010; Bright et *al*., 2017). Thirdly, research has shown that OSS promotes microbial diversity (Diedhiou-Sall et *al*., 2021; Mason et *al*., 2023) which includes microorganism that have plant growth promoting properties (Debenport et *al*., 2015).

Although rainfall was adequate both years of this study - a further factor in low rainfall years is the discovery that *P. reticulatum* performs hydraulic lift (HL) (Kizito et *al*., 2012), which is the movement of water along a water potential gradient of wet subsoil via roots to surface roots that release water to the dry surface soil. This happens at night when photosynthesis stops and stomata close (Dawson, 1993; Caldwell et *al*., 1998). The amount of water redistributed can go as high as 0.1 mm per day for *P. reticulatum* and 0.2 mm per day for *G. senegalensis* (Kizito *et al*., 2012). Bogie et al. (2018) proved that *G. senegalensis* through hydraulic lift "bioirrigates" adjacent millet plants – and since *P. reticulatum* also performs HL (Kizito *et al*. (2012) it would be expected it can also provide water for companion crops like cowpea.

These effects are consistent with other studies showing that improving soil quality increases crop yields (Sanou et *al*., 2010 and Bayala et *al*., 2015). Indeed, according to Diedhiou et al. (2009), the presence of shrubs and the incorporation of their residues improve soil quality by stimulating fungi which are critical for improving soil quality by forming macro-aggregates which promotes porosity, root penetration and water retention (Gupta and Germida, 1988).

Precipitation was 768 mm for 2021 and 1135 mm for 2022. The long-term mean rainfall for this research site is 750 mm which is close to the rainfall of 2021 but is considerably lower than the amount of precipitation for 2022. This could account for the lower yields in the high rainfall year of 2022. Iseki et al (2021) in Sudan had a similar result where the rainfall in the year that exceeded long-term average reduced cowpea yield. Their results suggested that excess rainfall inhibits N_2 fixation which in turn reduces cowpea yields.

The increased yield (670 %) due to +OSS averaged over years and varieties was much higher than the percent increase in 100 seed weight (2%). This indicates that OSS was increasing the number of seeds per plant over seed size.

Yields varied significantly between varieties in 2021 and 2022 with some clearly superior to others under OSS. The differential yield response of varieties to OSS could be due to differential physiological and phenotypic properties of each variety. Over the two seasons, Yacine had the best performance under the OSS using *P. reticulatum*. This is a large-seeded variety. Yacine is known for having wide climatic adaptability, a lower leaf area index (person. Comm, M. Diangar, 2024), shorter plant height (data not shown). It seems that a variety that minimizes competition with the shrub is important.

Mechanisms for this could be temporal offsets for when nutrients and water are taken up by the crop and the shrub. For example, differential spatial and/or temporal root growth or root architectural characteristics between inter-planted species may result in more efficient resource uptake by the crop (Henry et *al*., 2010; Postma and Lynch, 2012). Kizito et al. (2007), through water balance studies, showed that millet used water at the surface whereas shrubs remove water from deeper in the profile during the rainy season. Indeed, Bright et al. (2017) suggested another mechanism that explains lack of competition between *P. reticulatum* and crops—a temporal offset where crops primarily take up water and nutrients earlier in July to August where as for the shrub this uptake occurs later into September and October.

Although there were no obvious elevated disease or pest infestations on -OSS plots; suppression of both leaf and soil-borne disease incidence can be drastically reduced in mixed cropping (Stukenbrock and McDonald, 2008; Boudreau, 2013; Wuest et *al*., 2021). This can be due to host dilution or allelopathy (Ampt et *al*., 2019). Plasticity or the ability of a plant to morphologically adapt its phenotype to a particular condition, could be another mechanism where the balance between intercrop partners is attained through niche differentiation (Zhu et *al*., 2016). Optimization of mycorrhizal fungal common hyphal networks that directly connect the crop with the shrub could be another factor. Common mycorrhizal networks have been shown to drive the overyielding of plant species mixtures (Walder et *al*., 2012; Wang et *al*., 2020; Figueiredo et *al*., 2021).

Dry biomass results followed yield data, with +OSS cowpea biomass being substantially (40% on average) higher than the traditional management system (-OSS) in 2021 and 2022 (Table 2). This is important as cowpea biomass can be used for livestock fodder and is a valuable market product for small scale farmers of the Sahel. Indeed, in 2022, dry biomass production was higher in +OSS than in -OSS compared to 2021. From our study, a negative correlation between seed yield and dry biomass yield was observed. These observations would explain the gain in seed yield obtained in 2022 with *P. reticulatum*. The data suggest that the biomass production was reduced in favor of assimilate production for pod filling of the varieties. This was evident with Yacine as it produced lower biomass than the other varieties (data not shown).

5.0 PERSPECTIVES

The results showed that the OSS has a highly significant effect on seed production and most morphological growth properties of cowpea. The agro-morphological properties of cowpea height, collar diameter, grain yield, and dry biomass were all much greater for OSS when combined with *P. reticulatum* as the companion plant species. This overall improved performance with OSS can be attributed to the improved soil quality, nutrient efficiency, and water dynamics that has been noted in other studies (Dossa *et al*. 2009, 2010; Bright *et al*. 2017)., 2 Do. OSS incorporates large amounts of coppiced biomass (Bright *et al*., 2017) and the increased plant density of *P. reticulatum* causes greater root turnover – all of which contributes to the improved soils under OSS.

The best performing varieties in terms of grain yield under OSS were Yacine and Mouride in 2021 and Sam and Yacine in 2022 with Yacine being the most consistent performer. This could be due to its shorter stature/biomass and its specific ability to have compatible growth characteristic with *P. reticulatum.* The results are important for guiding famers in choosing cowpea varieties that are best suited for OSS when using *P. reticulatum*. Furthermore, the research provides a sound foundation for outreach and scaling of OSS for Senegal and other regions of the Sahel where *P. reticulatum* dominates.

OSS utilizes a local resource that is already available for small scale farmer adoption. Thus over coming green revolution technologies that require additional expenses and product distribution infrastructure. Utilizing OSS to increase cowpea production is important for food security that provides a nutritious and high protein food source for rural communities of the Sahel.

Future research is needed to screen varieties for other crops that perform the best under OSS management. Research is needed to determine which physiological properties such as root size and architecture, nutrient/water relations, mycorrhizal symbiosis, and so forth are important for optimal crop growth and yields under OSS. Furthermore, crop breeding could be pursued to specifically develop improved physiological traits for increased compatibility with shrubs and optimal crop productivity.

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