

Full Length Research Paper

Effect of *Piliostigma reticulatum* Intercropping on Crop Developmental Stages and Growth

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Abstract

Received 06 August, 2025; Revised 20 August, 2025; Accepted 21 August, 2025; Published 24 October, 2025

Yields of crops in the Sahel are well below the theoretical potential due to degraded soils from intensification of cropping, overgrazing, and scavenging for fuel wood. Local, biologically based systems that provide organic inputs are needed to address these agroecological challenges. The Optimized Shrub-intercropping System (OSS) utilizing *Piliostigma reticulatum* that has elevated density (~1500 shrubs ha⁻¹) where coppiced biomass is annually added to soil has been shown to remediate soils and increases crop yields. However, limited information is available on physiological and growth mechanisms of the two major crops in Senegal, pearl millet (*Pennisetum glaucum* (L) R. Br) and peanut (*Arachis hypogaea* L) under OSS. The objective was to determine the effect of interplanted *P. reticulatum* on crop development under varying rates of fertilizer in northern Senegal. The experiment (from 2013 to 2016) was a split-plot factorial design. The presence (OSS) or absence of *P. reticulatum* (no OSS management) was the main plot factor and fertilizer rate (0, 0.5, 1 or 1.5 times the recommended N-P-K rate) was the subplot factor. OSS increased, over no OSS, tiller/stem and leaf number in the drier years of 2014 and 2015 whereas millet height was higher for OSS over non-OSS across all years. Except for 2013, the presence of *P. reticulatum*—reduced days to millet and peanut maturity by 7 to 9 days. Correlation of crop physiological properties with yield provided evidence that mechanistically, the OSS yield response was related to increased millet tillering with OSS. The most dramatic benefits on crop growth response due to OSS occurred when there was greater water stress and at the zero fertilizer rate – shown with OSS increasing millet height by as much as 105 % (2015). The results also indicate OSS increases fertilizer efficiency. This shrub as the basis for OSS, is a locally available resource that can be readily used by subsistence farmers of the Sahel.

Key words: West Africa, agroforestry, Optimized Shrub Intercropping, millet, peanut, physiology, *Piliostigma reticulatum*

Abbreviations: Optimized Shrub Intercropping System (OSS); Days after sowing (DAS).

INTRODUCTION

Increasing demographic pressure on agricultural lands has led to natural resource and soil degradation in the Sahel (Maranz, 2009). This degradation lowers the capacity of the ecosystem to buffer against abiotic stress as a result of the loss of the arboreal component from the system; which is essential for proper ecological functioning by regulating soil temperature, soil humidity, nutrient storage and cycling (Bayala et al, 2014; Noordwijk et al, 2014). As a result, soil quality is now declining in the Sahel, resulting in decreasing soil organic matter, nitrogen and phosphorus (Mafongoya et al, 2006). This has led to a general decline in agricultural production and increased food insecurity and poverty, especially in rural areas (World Food Programme, 2018).

Improving soil quality and sound management of natural resources to restore the productivity of agricultural land is imperative for reducing food insecurity and improving the living conditions of rural populations in the Sahel (Bationo and Buerkert, 2001).

Agroforestry systems are increasingly considered to be one of the best solutions to address this challenge, due to numerous advantages reported by several works. Indeed, the presence of woody species in cropped fields of Africa, known as the Parkland system, provides provisioning and cultural ecosystem services (Bayala et al, 2014; Sinare and Gordon, 2015), that is recognized by farmers who manage them to maximize economic returns (Tschakert et al., 2004; Bayala et al, 2010; Faye et al, 2011; Fifanou et al, 2011). Parkland agroforestry is a recognized conservation agriculture (CA) practice (Giller et al, 2009; Bayala et al, 2012; Mason et al, 2015) that is promoted to increase food security (Garritty et al, 2010; Mbow et al, 2014) and carbon (C) sequestration for the region (Lal, 2004; Verchot et al, 2007; Takimoto et al, 2008).

Over the recent past there has been recognition that indigenous shrubs within farmers' fields of the Sahel provide significant benefits to soils and crops (Bright et al, 2017, 2021; Lufafa et al, 2008a; 2009). These shrubs are normally pruned back to the soil surface (coppicing), and the residue is burned in the spring prior to cultivation, but if left uncut they will continue to grow (Manlay et al, 2002a; b; Tschakert et al, 2004; Woome et al, 2004; Seghieri et al, 2005).

However, an alternative management is the Optimized Shrub-intercropping System (OSS), which involves increasing shrub density of current levels (approximately <200 to 350 shrubs ha⁻¹) (Lufafa et al, 2009) to 1200 to 1500 shrubs ha⁻¹ and rather than burning the coppiced residue, it is incorporated into soil near the beginning of the rainy season before planting (Bright et al, 2017; 2021). This shrub system has been developed with the shrub species, *Guiera senegalensis* (Bright et al, 2021) as well as *Piliostigma reticulatum* (Bright et al, 2017).

Shrub based intercropping with millet or peanut has been shown to improve water availability for crops (Kizito et al, 2006; Kizito et al, 2007; Kizito et al, 2012; Bogie et al, 2018a), soil quality (Dossa et al, 2013; Bright et al, 2017; 2021), carbon storage (Lufafa et al, 2008), fertilizer efficiency, nutrient recycling and crop yields (Dossa et al, 2013; Yélémou et al, 2013; Bright et al, 2017; 2021), soil biodiversity and biological activity (Diedhiou-Sall et al, 2013; Debenport et al, 2015; Hernandez et al, 2015; Diakhate et al, 2016; Mason et al, 2023). Utilizing shrubs as a local resource enables farmers to adopt OSS and capture the ecological and agronomic benefits.

These ecological and soil services provided by OSS are reflected in the dramatic yield response by OSS (Dossa et al, 2012; 2013; Bright et al 2017; 2021). The crop response due to OSS was investigated on *G. senegalensis* by Bayala et al (2021) showing many crop growth and physiological responses to this shrub species under OSS management. However, no information is available with *P. reticulatum* as the companion plant in OSS management on crop developmental stages and growth. This is of particular importance in the Sahel where erratic rainfall, in-season drought and expected shortening of the rainy season with climate change.

Therefore, the objective of this study was to determine the effect of the presence or absence of *P. reticulatum* with OSS management under varying rates of fertilizer on crop phenology, number of leaves, number of stems and growth.

MATERIALS AND METHODS

Experimental site

The research was conducted on the long-term *P. reticulatum* intercropping experiment located near Niore, in Senegal; in the southern Peanut Basin (13°45'N, 15°47' W), within the Northern Sudanian climatic region that is semi-arid (Sarr et al, 2013). The elevation is 18 m above sea level, with 0-2% slopes and a savanna ecosystem predominates with trees and shrubs frequently growing together in farmers' fields. *Piliostigma reticulatum* was the dominate woody species found in farmers' fields with densities ranging from 134 to 288 shrubs per hectare (Lufafa et al, 2008). *Piliostigma 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; but anchored by a thick, woody tap root that branches and provides access to ground water (Kizito et al, 2006). Typically, the shrub crown height is 1 m high by 1 - 2 m in diameter, and has multiple shoots. 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). Atmospheric temperatures range from 20.0 to 35.7 °C; while mean annual precipitation is 750 mm, mainly coming between July and September. The research was carried out in the peanut basin of Senegal in West Africa, which is semiarid and has most of its precipitation distributed from June to October, generally as intense short-duration showers. This region has unimodal rainfall, 700 mm per annum and a mean annual temperature of 32 °C.

This region has unimodal rainfall, 700 mm per annum and a mean annual temperature of 32 °C. Specifically, the study was conducted at Nioro, Senegal (N13°45' W15° 47'), a region where *Piliostigma reticulatum* dominates and has a sandy, lateritic soil classified as an Oxisol (FAO, 1998). The top of water table is approximately 8 m at the research site. The cumulative annual rainfall at the site was 634.3, 513.3, 658.7 and 735 mm in 2013, 2014, 2015, and 2016, respectively (Fig. 1). Precipitation was recorded with a tipping bucket rain gauge at 2 m (TR-525-M, Texas Electronics, Dallas, TX).

The experiment was conducted under rainfed conditions as is the case for all farmer grown millet and peanut production in Senegal.

Experimental Design

A field of approximately 0.5 ha with preexisting shrubs that had been under local farmer management for at least the last 50 years was selected. The experiment had a completely randomized block and split plot design (4 replications) with shrub presence (plus and minus) as main plot (46 m x 4.5 m) and fertilizer rate as sub-plots (10 x 4.5 m) (Dossa et al, 2013).

Eight main plots were established in the winter of 2003, where half of the plots had all shrubs removed manually (shrub plots) and the other half retained the existing shrubs with some plots receiving shrub seedlings to increase the density, randomly but evenly distributed. This resulted in densities ranging from 889 to 1111 shrubs ha⁻¹ with an average density of 1000 shrubs ha⁻¹ across all OSS plots. Within each main plot, 4 subplots were established with a 2-m gap between subplots and a 3-m gap between main plots. Following the dominant farming practices in the region, all plots had a crop rotation of peanut (*Arachis hypogaea* L, variety 73-33) and millet (*Pennisetum glaucum* (L) R. Br., variety Souna 3). Peanut was planted at a spacing of 15 cm within rows and 50 cm between rows, generating a density of

approximately 130,000 plants ha⁻¹. During the summers of 2013, 2015 and 2016, pearl millet was planted in all plots at a spacing of 90 cm within rows and 90 cm between rows; leading to a population density of 12,345 plants ha⁻¹.

The subplot fertilizer treatments were 0, 0.5, 1.0 or 1.5 times the recommended fertilizer rate for each crop. For peanut, the recommended rate was 9 kg N, 30 kg P and 15 kg K ha⁻¹, which was manually broadcast after peanut germination followed by hand hoeing and incorporation to a depth of 5 to 8 cm. Peanut (var. 73-33) was planted in 2014 at a density of approximately 130,000 plants ha⁻¹. The recommended fertilizer rate for millet was 22.5 kg N, 15 kg P and 15 kg K ha⁻¹ which was applied at planting followed by 46 kg N ha⁻¹ as urea (split of 23 kg 15 days and 45 days after planting). During the summers of 2013, 2015 and 2016, millet (var. Souna 3) was planted in all plots at densities of 12,345 plants ha⁻¹. Each year, before the rainy season started in June, the shrubs were coppiced and cut into 5- to 10-cm pieces before these residues were spread evenly over the OSS plots. The residue was incorporated in June or early July with shallow sweep cultivator. This stands in contrast to the current management of *P. reticulatum* in this region, which consists of burning the coppiced biomass prior to planting (Dossa et al, 2013). Crop planting occurred each July, and during the cropping season, shrubs were coppiced twice per growing season, and residues returned to the soil surface. Shrubs regrew during the dry season when there was no weeding of the plots. This sequence of management was maintained up to and including 2013 to 2016 during the data collection for this paper.

Crop phenology and growth measurements

Phenology observation was carried out weekly on the same plants. Millet flowering stage was monitored on 15 central plants of each plot. The date of 50% millet flowering was reached when half of the panicles had bloomed. For peanut, because of its short-lived flowers, gynophore emission was considered the reproduction phase. Additionally, the date of 50% gynophore emission of peanut was recorded when half of the plant reached this stage.

Plant height development of the crops was determined by measuring from the soil surface to the base of the latest leaf on the main stem. Crop growth was monitored weekly on 5 plants in the middle row of each subplot. For millet, measurements occurred from the vegetative to reproductive stage (stem elongation) marked by panicle initiation (Maiti and Bidinger, 1981).

The number of stems and leaves of crops were determined at the reproductive initiation phase. Number of stems and leaves on the main stem of 5 plants in the

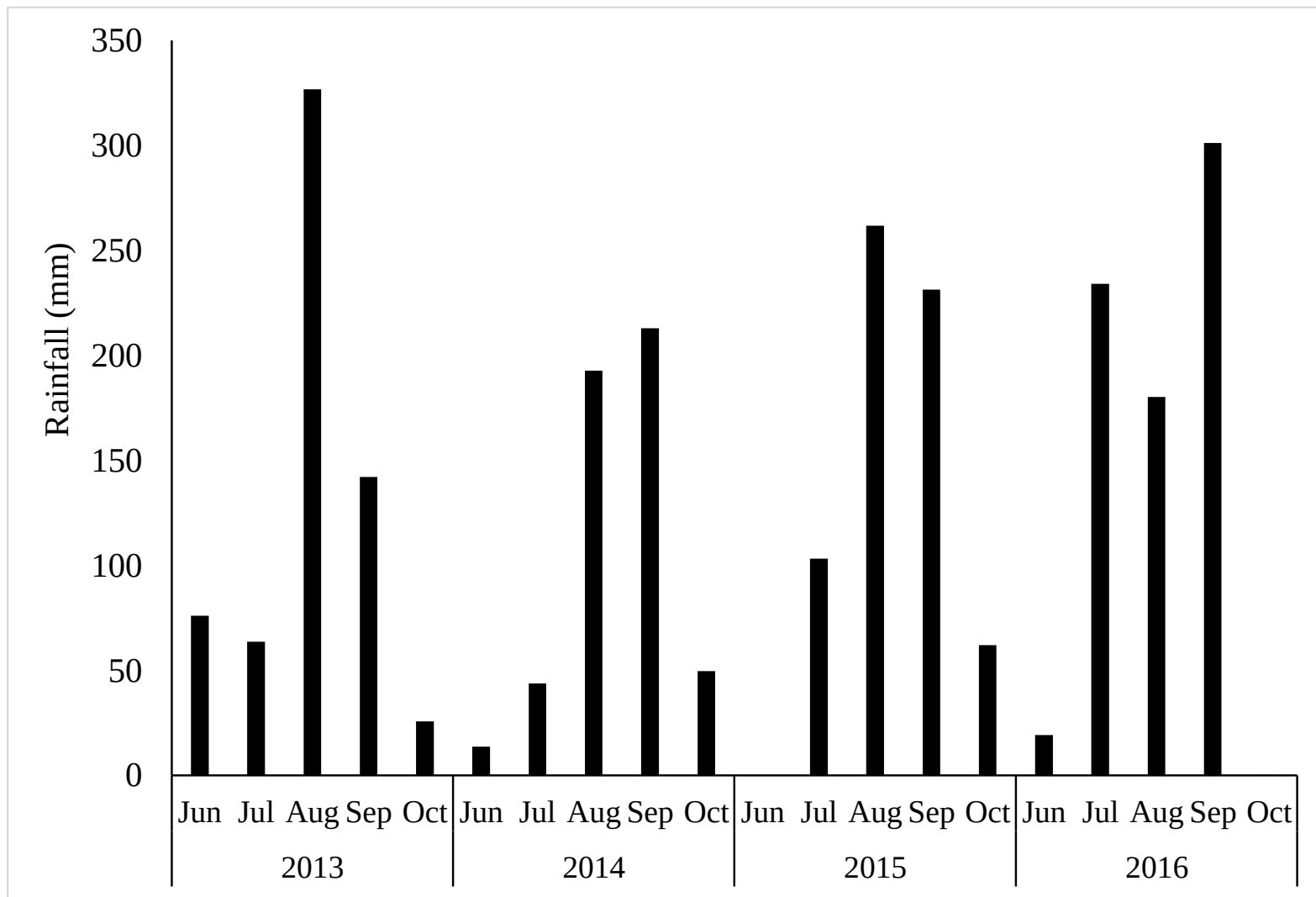


Fig. 1: Nioro rainfall distribution.

middle row of each subplot were counted.

The procedures for yield data used for correlation to crop growth properties is fully described Bright et al (2017). In brief, each October at crop maturity, the inner two-thirds of each subplot was harvested. For peanut, the entire plant was harvested followed by 4 to 5 days of sun drying and then pods removal and weighing. Pearl millet panicles were removed and air-dried to <10% water content; followed by millet seed separation and weighing.

Statistical Analysis

The R v 3.02 (<http://www.R-project.org/>; R Core Team, 2014) statistical software was used to analyze the split-plot design data. Presence or absence of shrubs, and fertilizer rate were analyzed as fixed effects and blocks as a random effect for all parameters measured. A two-way ANOVA was used to analyze plant growth parameters at each measurement date. Differences were considered significant at $P < 0.05$, and Tukey's honest significant difference test was used to separate significant effects by fertilizer treatment. ANOVA assumptions were tested and data was normally distributed. Although not always significant at $P < 0.05$ interactions across the measured properties tended to have high probabilities, and as such data is presented as single factor effects to enable more nuanced data presentation.

RESULTS

The most significant effects of OSS on millet in particular were number of stems and plant height. And this was most evident at the zero fertilizer rate when OSS had the most dramatic results. The results are presented in detail below.

Phenology

The reproduction phase on millet for 2015 and 2016 had a non-significant ($P < 0.05$) effect of OSS reducing days to flowering by 3 to 9 days (Table 1). Furthermore, increasing fertilizer rates decreased days to 50 % flowering on millet. In other years with no fertilizer, the results showed that the reproduction phase of the crops varied over time. Indeed, in 2014, peanut gynophore emergence occurred 7 days earlier in the presence of shrubs. However, none of these differences were significant at $P < 0.05$ due to high replication variability.

Number of stems

Shrubs did not always affect crop development the same as fertilizers (Table 2). In 2013, there was no effect of shrubs ($P > 0.66$), but fertilizer application ($P < 0.01$) and the shrub x fertilizer interaction had significant effects on

the number of millet tillers ($P < 0.01$). The maximum number of tillers (15.2 tillers) was produced in the plots with no shrubs combined with a 1.0 fertilizer rate. The shrubs significantly affected the number of peanut stems in 2014 ($P < 0.05$) and number of millet tillers in 2015 ($P < 0.05$). The number of peanut stems in the shrub plots was 76% higher than that in the no shrub plots. However, in 2016, in the presence of shrubs, the production of tillers was not significant ($P = 0.74$). Fertilization had a significant effect on the production of tillers. The shrub x fertilizer interaction was not significant from 2014 to 2016. In 2015 there was a significant effect of overall shrub effect on number of millet tillers but not when averaging across fertilizer rates for 2013 and 2016. However, with the zero fertilizer treatment, millet intercropped with shrubs had a significantly higher millet tiller or peanut stem counts than the non-OSS plots for all 4 years (Table 2).

Number of leaves

The number of millet leaves was not affected by shrubs in 2013 or 2016 (Table 3). However, for 2014 and 2015, fertilizer rates significantly ($P < 0.05$) affected the number of peanut and millet leaves in both years. In the plots with shrubs, the millet leaf number was significantly higher than no shrubs. Additionally, fertilizer application significantly affected number of crop leaves in 3 out of 4 years. The shrub x fertilizer interaction was significant ($P < 0.05$) only for millet in 2015. The number of leaves on the crop plants increased when the fertilizer rate increased.

Effect of *P. reticulatum* on crop growth

In 2013 (Fig. 2), the millet height was affected by shrubs during the cropping season except at 60 days after sowing (DAS) ($P < 0.15$). The effect of fertilizer on millet height was significant ($P < 0.001$) from 45 to 75 DAS. The effect of shrub only (OSS-Fertilizer) was statistically the same as that of the plot with fertilizer. At 75 DAS, millet height varied from 169 to 201 cm in the shrub treatment for the control and fertilizer treatments. In the no shrub plot, the millet height ranged from 122 to 184 cm for the control and fertilizer treatments, respectively.

Peanut growth (2014) was not affected by either shrubs or fertilizer at 11 or 25 DAS (Fig. 3). The effect of the shrubs was significant ($P < 0.05$) at 32 DAS and further increased up to 67 DAS ($P < 0.01$). During peanut growth, the shrub-only plot and shrub combined with fertilizer (OSS-Fertilizer) patterns were very similar across all measurement days. The height of peanut plants in these treatments increased significantly and reached 26 cm at 67 DAS, which was taller than the other treatments. Indeed, the heights of plants in the non-OSS

Table 1: Days to early reproduction stage of millet or peanut over four growing seasons (no significant differences at $P < 0.05$).

Fertilizer rate	2013 Millet Flowering		2014 Peanut Gynophores		2015 Millet Flowering		2016 Millet Flowering	
	OSS	-OSS	OSS	-OSS	OSS	-OSS	OSS	-OSS
	-----Days-----							
0	74	74	32	39	29	32	73	82
0.5	ND†	ND	ND	ND	25	28	61	65
1.0	67	67	39	39	24	25	62	65
1.5	ND	ND	ND	ND	24	25	61	64

†Not determined.

Table 2: Number of tillers and stems of millet or peanut over four growing seasons.

Fertilizer rate	2013 Millet Tillers		2014 Peanut Stems		2015 Millet Tillers		2016 Millet Tillers	
	OSS	-OSS	OSS	-OSS	OSS	-OSS	OSS	-OSS
0	13.2a	9.8b	10.9a	7.4b	10.2a	8.4b	6.2a	3.6b
0.5	ND†	ND	ND	ND	14.6a	12.2b	8.7a	7.2a
1.0	13.1a	15.2a	11.5a	9.7b	16.0a	14.0b	9.2a	9.3a
1.5	ND	ND	ND	ND	15.1a	15.3a	11.9a	11.7a
Mean	13.1a	12.5a	11.2a	8.5b	13.9a	12.5b	8.6a	8.3a

Probability			
Shrub (OSS)*	0.660	0.04	0.043
Fertilizer (F)	0.003	0.01	0.001
OSS X F	0.002	0.12	0.188

* Pairs of values in a year and row with the same lower case letters are not significantly different at $P < 0.05$.

†Not determined.

+Fertilizer treatment and plants in the non-OSS - Fertilizer were 19 and 16 cm, respectively.

Millet height was significantly affected by the shrub ($P < 0.05$) and fertilizer ($P < 0.01$) factors in 2015 over the whole cropping season (Fig. 4). There was a synergistic effect of combining shrubs and fertilizer which increased millet growth between 7 and 28 DAS. After this date, variations in millet growth properties stayed constant until 56 DAS. Millet height in the shrub plots with any fertilizer rates reached approximately 225 cm.

Without shrubs, the growth of millet in 2015 was also rapid between 7 and 28 DAS. Millet height was significantly affected by fertilizer rates. After this period up to 56 DAS, there was a low growth rate non-OSS/-Fertilizer in millet height. The highest millet height was obtained with 1.0 and 1.5 fertilizer rate with the latter

reaching 211 cm. Millet height in the non-OSS/-Fertilizer treatment was 91.5 cm at the end of the crop season.

In 2016, millet height was significantly affected by shrubs ($P < 0.05$) at 71 DAS (Fig. 5). However, the fertilizer effect was significant ($P < 0.05$) at 43 and 64 DAS ($P < 0.01$) for the other dates. In shrub plots, millet height was 2 times higher with 1.0 and 1.5 fertilizer rates than with 0 and 0.5 fertilizer rates at 57 DAS. The results also showed that at 71 DAS, the millet height without fertilizer was 86.5 cm and with a 0.5 fertilizer rate (143 cm) was statistically similar to the millet height with the other fertilizer rates (173 cm) ($P < 0.05$). Without shrubs, the low rate of fertilizer on millet produced the highest height as the rate of fertilizer increased. At 71 DAS, the millet plants in the fertilizer plot were 3 times taller than the millet plants in the non-OSS/-Fertilizer.

Table 3: Effect of OSS and fertilizer on millet or peanut leaf counts.

Fertilizer rate	2013 Millet		2014 Peanut		2015 Millet		2016 Millet	
	OSS	-OSS	OSS	-OSS	OSS	-OSS	OSS	b-OSS
0	8.6a	7.7a	14. a	12.5b	10.4a	7.6b	7.8a	5.9a
0.5	ND†	ND	ND	ND	11.4a	9.9a	8.8a	7.6a
1.0	9.5a	9.1a	14. a	12.7b	11.3a	11.0a	8.0a	8.2a
1.5	ND	ND	ND	ND	12.1a	11.5a	9.1a	8.1a
Mean	9.0a	8.4a	14.7 a	12.6b	11.3a	10.0b	8.4a	7.5a
Probability								
Shrub (OSS)*	0.119		0.001		0.020		0.163	
Fertilizer (F)	0.001		0.451		0.001		0.008	
OSS X Fertilizer	0.291		0.152		0.026		0.153	

*Pairs of values in a year and row with the same lower case letters are not significantly different at $P < 0.05$.

†Not determined.

In both 2015 and 2016 at the zero fertilizer rate the +OSS treatment produced substantially greater millet plant heights over -OSS when *P. reticulatum* was absent.

DISCUSSION

Although statistically not significant at $P < 0.05$, there was a trend to reduce days to 50% flowering for millet (3 to 9 days for millet in 2015 and 2016) (P values ranged from 0.49 to 0.88 for the management effect), which was consistent with a companion paper where *Guiera senegalensis* was the shrub being intercropped in the OSS (Bayala et al, 2021). They showed a decrease to 50 % flowering of 7 days on millet. This is very important for increasing water efficiency in the case of high atmospheric water vapor demand that leads to rapid drying of root-zone soil during pauses in rainfall (Bogie et al 2018a). The current study at Nioro is in the southern region of the Peanut Basin which has more favorable growing conditions with higher rainfall and higher quality soils that have greater clay content than northern part of the Peanut Basin where *G. senegalensis* dominates (Lufafa et al, 2008). Thus, since the current study had the most significant OSS response in the drier years (2014 and 2015), this result and the report of Bayala et al (2021) lends support to the idea that shrubs have their biggest impact in more stressful environmental conditions. As discussed below there are a number of potential mechanisms for OSS to assist crops facing deficient water conditions.

The Optimized Shrub-intercropping System (OSS) increased tiller/stem and leaf number in the drier years of 2014 and 2015 whereas millet height was higher for OSS over non-OSS across all years. This is consistent to another study of OSS that used *Guiera senegalensis* as the companion shrub in OSS and was conducted in the

more northerly cropping region of Senegal (Bayala et al, 2021).

Overall, the presence of *P. reticulatum* shrubs across various phenological measurements developed more rapidly or showed improved growth over the absence of the shrubs, most notably at the zero fertilizer rate. Previous research provides insights into how OSS, with *G. senegalensis* or *P. reticulatum* as companion plants improve crop response in general and specifically under low rainfall and water stress (Dossa et al, 2012; 2013 Bright et al, 2017, 2021).

Yield data presented by Bright et al (2017) at the same study site as the current study followed growth parameters with a significant +OSS effect overall (except 2013 in the 1.0 NPK fertilizer rate). All four cropping years there was a significant effect ($P < 0.05$) on the main plot treatment of OSS.

There is some evidence as shown in the Table 4 with correlations, that the physiological mechanism by which OSS increases millet yields is the number of tillers that ultimately translates into the number of panicles and greater yield.

The improved growth of plants in the presence of *P. reticulatum* can be attributed to a number of mechanisms. First, it has been shown that OSS improves soil quality. This includes increasing nutrient availability (Dossa et al, 2008, 2010, 2012; Bright et al, 2017) and soil organic matter that promotes C sequestration (Bright et al, 2017; 2021). Furthermore, this system increases microbial biomass and diversity (Diedhiou et al, 2013; Debenport et al, 2015; Diedhiou et al, 2021), with evidence that *P. reticulatum* under OSS promotes beneficial microorganisms (Debenport et al, 2015).

Second, OSS under *P. reticulatum* offsets low water availability for crops, as evidenced with the most dramatic and extensive effect on crop physiological properties

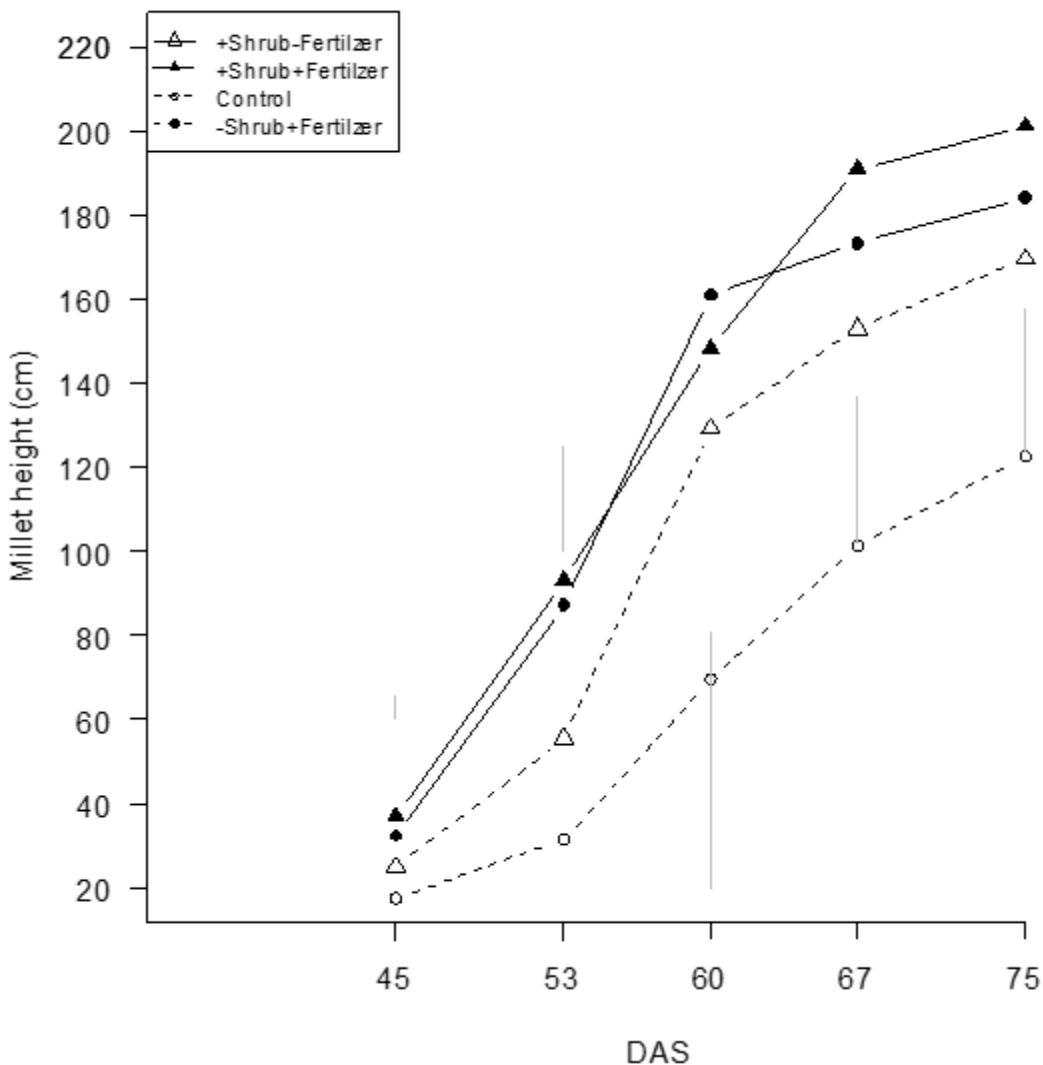


Fig 2: Effect of OSS and fertilizer on millet plant height over the 2013 season in Days after Seeding (DAS). Vertical bars are means separation difference at $P<0.05$.

occurring in the low rainfall years of 2014 and 2015. Mechanistically, this can be attributed to the improved soil quality described above resulting from the high amounts of shrub biomass that is incorporated into soil under OSS (Bright et al 2017; 2021). Adding organic matter inputs to soils corresponds to improved physical properties by increasing aggregation and soil porosity that in turn increases water storage and availability to crops (Pennell et al, 1984; Michels et al, 1995; Snapp et al, 1998; Kong et al, 2005).

However, there is another profound mechanism of OSS that reduces water stress. This is the discovery that both *G. senegalensis* and *P. reticulatum* perform

hydraulic lift (Kizito et al, 2012). This occurs during the night when stomata close and evapotranspiration stops, that results in the movement of water from wet subsoil, via deep roots, to the surface roots that release water to the soil (Richards and Caldwell, 1987). Bogie et al, (2018) using labeled water, showed that *G. senegalensis* via hydraulic lift “bioirrigates” adjacent millet plants. Another factor is a reduction in competition for nutrients and water by *P. reticulatum* roots because it preferentially extracts water from deeper soil layers (Kizito et al, 2006) compared to crops that concentrate roots at the soil surface. Other benefits are that high inputs of coppiced shrub biomass produces a litter layer on the soil surface

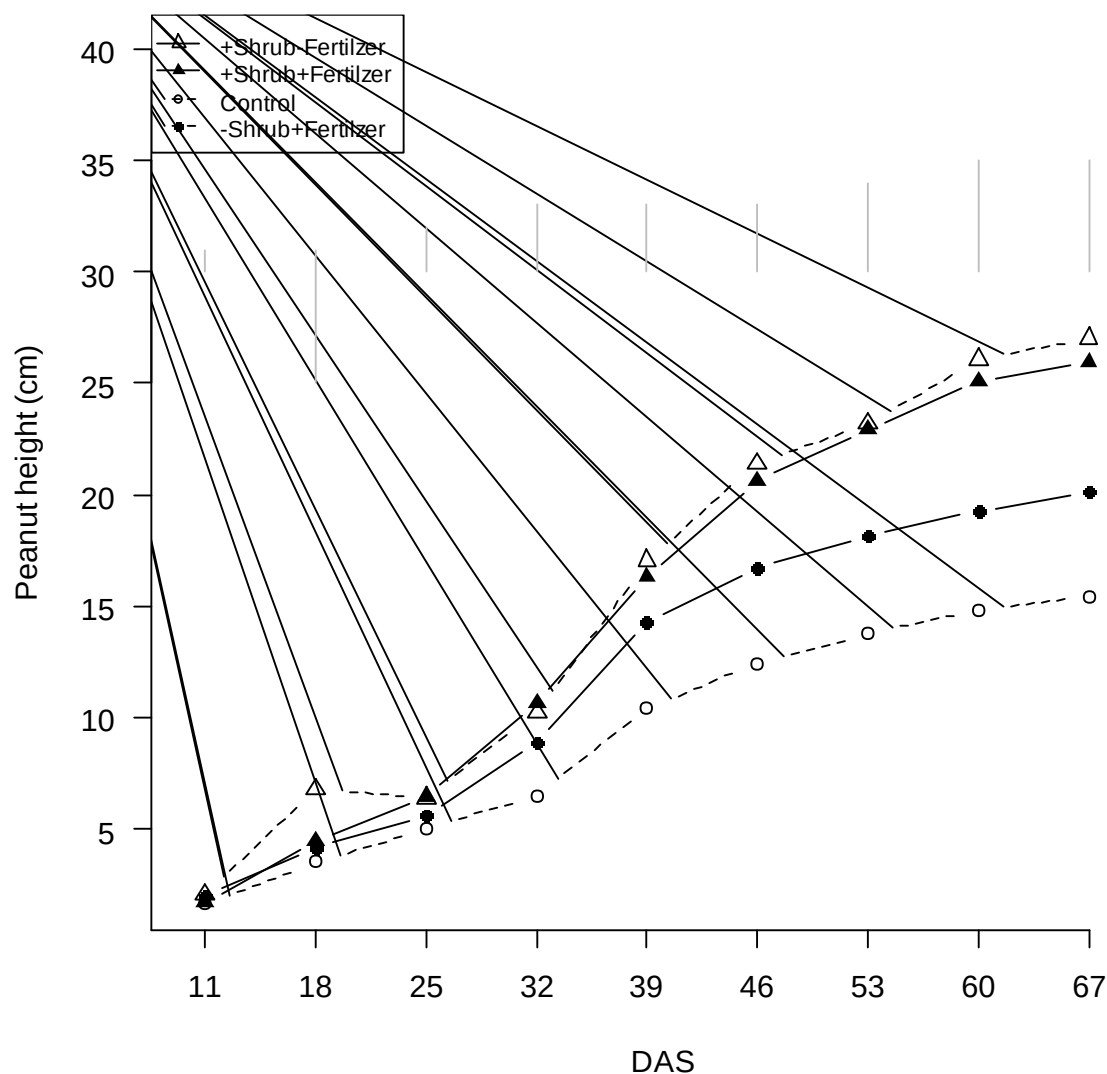


Fig. 3: Effect of OSS and fertilizer on peanut plant height over the 2014 season in Days after Seeding (DAS). Vertical bars are means separation difference at $P < 0.05$.

that reduces evaporation, and air and soil temperatures, providing a favorable microclimate over just bare soil (Trail et al, 2016; Bogie et al, 2018a).

Thus, the improved crop physiological properties (e.g. plant height and millet tillers and peanut stems) with OSS using *P. reticulatum* in the drier years (2014 and 2015) can be attributed to the improved soil quality, hydraulic lift and reduced shrub-crop water competition (Dossa et al, 2008, 2010, 2012; Kizito et al, 2008, 2013; Bogie et al, 2018a,b; Bright et al, 2017). This effect is consistent with the findings of other studies showing that shrubs have potential advantages for conservation agriculture and are solutions for landscape remediation and the low yields of rainfed crops in the Sahel (Wezel et al, 2000; Leenders et al, 2007; Lufafa et al, 2008).

Crop growth was significantly improved by the NPK fertilizer in this study. However, the highest crop growth properties were with the synergistic effect of OSS in combination with NPK fertilization. Crop growth conditions are improved by OSS by increasing soil quality (e.g. aggregation, porosity and organic) and water availability that in turn promotes NPK efficiency. Increasing soil organic matter also provides a substrate for soil microorganisms and fauna, thus increasing their activities in the soil that can promote crop growth (Diedhiou-Sall et al, 2013; Debenport et al, 2015; Hernandez et al, 2015; Mafongoya et al, 2016).

In this study, millet height was significantly affected by fertilizer combined with the presence of shrubs during all years of the experiment. However, applying a minimum

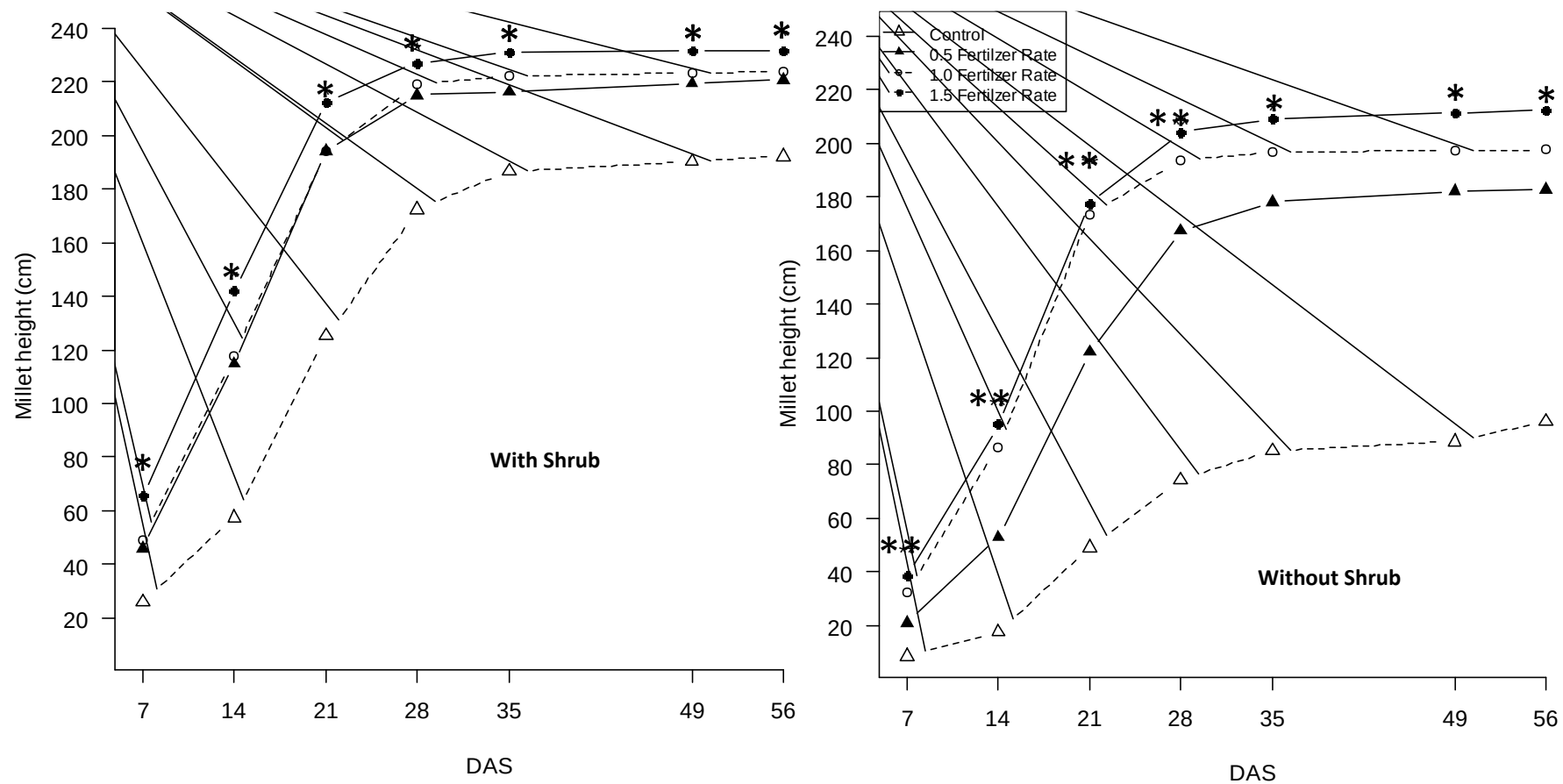


Fig. 4: Effect of OSS and fertilizer on millet plant height over the 2015 season in Days after Seeding (DAS).

*Significant soil management treatment effect within a sampling date at $P < 0.05$.

**Significant soil management treatment effect within a sampling date at $P < 0.01$.

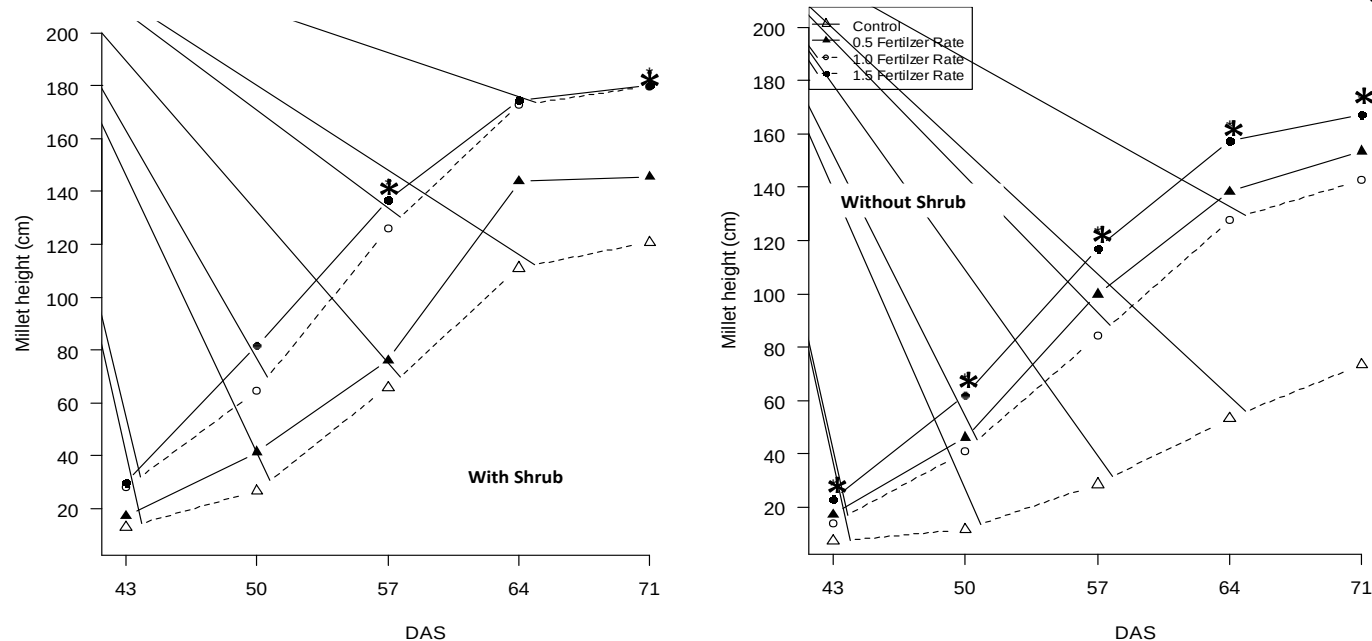


Fig. 5: Effect of OSS and fertilizer on millet plant height over the 2016 season in Days after Seeding (DAS).
 *Significant soil management treatment effect within a sampling date at $P < 0.05$.

Table 4: Correlation coefficients of peanut or millet growth parameters with crop yields (yield data from Bright et al, 2017, Table S1).

	Millet 2013	Peanut 2014	Millet 2015	Millet 2016
	-----r-value-----			
Leaf Count	-0.08	0.41	0.12	0.59
Plant Height	0.29	ND†	0.35	0.61
Tiller or Stem Count	0.45	0.48	0.12	0.60
Panicles	ND†	ND†	0.85	ND†

†Not determined

fertilizer rate ($0.5 \times$ fertilizer rate) affected crop height similarly to the maximum rate of fertilizer ($1.5 \times$ fertilizer rate). The ability of OSS to provide nutrients was shown by the result that even without NPK, OSS produced substantially taller millet plants than the -OSS treatment in 2015 and 2016 (Figs. 4 and 5).

Previous research provides evidence that supports the above results that shrubs improve water and nutrient use

efficiency by recycling nutrients in their biomass (Mafongoya et al, 2016; Bright et al, 2017; 2021). This suggests that the presence of shrubs could enable the reduction of fertilizer use for crops. This is consistent with the findings of Dossa et al (2010), who found *P. reticulatum*, creates islands of fertility with higher nutrient levels beneath than outside the canopy.

The results provide a crop physiology and growth mechanism understanding for the strong OSS yield response found in previous research (Dossa et al., 2013; Bright et al., 2017). Thus, providing a selection or breeding guide based on plant properties of millet or peanut to further enhance OSS productivity. Intercropping with a shrub and *P. reticulatum* in particular, where coppiced residues are amended to soils, presents a workable option for small farmers in sub-Saharan Africa as it is a local resource that is dominant across the Sahel and requires very little maintenance (Bright et al., 2017).

PERPESCTIVES

The objective of this study was to determine the effect of the presence of *P. reticulatum* at elevated densities compared to when *P. reticulatum* was absent under varying rates of fertilizer on crop phenology and growth. A limitation of the experiments was the tendency for high variability, which in some cases limited the ability of ANOVA to detect treatment effects – even though there were significant observational differences in treatment means. This was true for the temporal results which had a non-significant trend for millet to reach the reproductive stage 7-9 days earlier with OSS than the control.

In the years with lower rainfall OSS had its biggest impact on crop growth (plant height) response at the zero fertilizer rate – shown with OSS increasing millet height by as much as 105 % (2015) ($P < 0.05$). It was also shown at 71 DAS, that millet height without fertilizer was 86.5 cm and with a 0.5 fertilizer rate (143 cm) which was statistically similar to the millet height with the other fertilizer rates (173 cm) ($P < 0.05$). Although this needs to be further investigated across diverse soils and environments, it suggests OSS increases fertilizer efficiency and that less fertilizer is needed in the Sahel for millet. This is a very beneficial property for subsistence farmers who use little or no inorganic fertilizer. Furthermore, *P. reticulatum* is a locally available resource for farmers of the Sahel.

Our results provide convincing evidence that shrubs, as managed in the present study, are not competitive with crops, and indeed significantly improved crop growth which from previous research can be attributed to OSS promoting water/nutrient dynamics and higher soil quality (Kizito et al, 2007; Dossa et al, 2012; Dossa et al, 2013; Bright et al, 2017; 2021). Additional research is needed to determine the optimal shrub densities and interactions with tree species for further yield improvement, including the amount of recharge to groundwater that happens below the rooting zone. However, the outcomes of this study combined with supporting reports on specific components of the *P. reticulatum* intercropping system (Kizito et al, 2007; Lufafa et al, 2008; Diedhiou-Sall et al, 2013; Yélémou et al, 2012; Bright et al, 2017) provide a

solid foundation to launch farmer participatory projects to pilot test, demonstrate, and targeted scaling (with technical backstopping) of this optimized *P. reticulatum* system throughout the Sahel. The OSS system addresses the chronic challenge of food insecurity in the Sahel and a crop management system adoptable by smallholder farmers to enable adaptation to climate change.

Acknowledgments

This research was supported by a National Science Foundation Partnership for International Research and Education (PIRE) grant (NSF 0968247). We thank Ababacar Ndiaye (UCAD), Abdoukarim Kéita (UGB), Moussa Dione, and Bara Diagne of ENSA for helping in data collection. Also to Dame Sy for important contributions to field work.

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