Long-term *Piliostigma reticulatum* Intercropping in the Sahel: Crop Productivity, Carbon Sequestration, Nutrient Cycling, and Soil Quality

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Abstract

Throughout the Sahel, food insecurity remains a persistent threat. A few studies have shown that *Piliostigma reticulatum*, a dominant native shrub in parklands from Senegal to Sudan, can positively impact crop yields. However, there are no experiments that measure whether this species can stabilize long-term crop productivity under erratic rainfall. Therefore, an 11-year study of an optimized *P. reticulatum* intercropping system (1000 shrubs ha⁻¹ with annual coppiced residue soil amendments) was initiated in 2004 in Senegal, West Africa to determine its impacts on crop productivity and soil quality. The experiment was a split-plot factorial design with the main plot shrubs (with and without) and the subplot fertilizer rate (0, 0.5, 1, and 1.5 times the recommended N-P-K rate) with an annual groundnut (*Arachis hypogaea*) and pearl millet (*Pennisetum glaucum*) crop rotation. Yield, biomass, soil carbon, and soil and plant nutrient data from 2011-2015 were compared with data from 2004-2007. The presence of shrubs increased millet and groundnut yield from 2011-2015 and rainfall water use efficiency (WUE) between 2004 and 2015. Without fertilizer addition, the shrub plots had approximately 2 times greater millet yield throughout the duration of this experiment. The presence of shrubs also improved soil quality, as evidenced by significantly greater C in the fraction <53 µm and total C in shrub over non-shrub plots. Thus, *P. reticulatum* intercropping promotes C sequestration. In addition, five macronutrients (N, K, Ca, Mg, S) and two micronutrients (Mn and Cu) were significantly greater in the shrub plots. The results provide strong evidence that intercropping with *P. reticulatum* is an ecological agroforestry system for the Sahel that can remediate soils, increase crop yields, and buffer climate change.

Keywords: West Africa, Parklands, Agroforestry, Shrub intercropping, Pearl Millet, Groundnut

1. Introduction

Challenges abound for crop production in the Sahel—recurring drought, land degradation, sandy soils with poor natural soil fertility, low investment in crop breeding, and limited use of fertilizers (Bationo et al., 2007; Sultan et al., 2013; Epule et al., 2014; FAO and ITPS, 2015; Pucheret et al., 2016). Most small-holder farmers rely on manure to maintain soil fertility, and across the continent the average fertilizer input is 8 to 10 kg ha⁻¹ which accounts for less than 1% of global usage (Garrity et al., 2010; Turner and Hiernaux, 2015). Thus, to address the challenges for food security in the Sahel, agroecosystems are needed that are ecological and use local resources.

Conservation agriculture (CA) practices (Bayala et al., 2012; Lahmar, 2012; Mason et al., 2015a) are frequently proposed to increase soil quality and crop yields. These include: 1) minimal or no tillage; 2) green manure; 3) mulching or maintaining soil cover; 4) diversified crop rotation; 5) planting crops under woody trees or shrubs. However, in a review by Bayala et al. (2012), there was high variability in the yield response associated with these practices across the Sahel, and most of them have limited potential for wide-scale adoption. For example, in the case of mulching or manure, typically quantities are insufficient (Badiane et al., 2000) or the labor and time expenses are too great to be practical for the majority of subsistence farmers (Bayala et al., 2012). Moreover, crop or other residues frequently have greater value as animal feed, fuel or construction materials over addition to soils (Mason et al., 2015a; Valbuena et al., 2015). The use of green manures is dependent on sufficient rainfall (Bayala et al., 2012). Woody vegetation improves soil quality, but often that does not translate into greater crop yields (Gnankambary et al., 2008; Bayala et al., 2012, 2015; Sinare and Gordon, 2015). In summary, in order for a CA technique to be implementable in the Sahel, it must not only improve yields but

also be integrally connected to the ecology and socioeconomics of the region (Knowler and Bradshaw, 2007).

The Sahel is predominantly characterized by parkland agroforestry where farmers allow trees to remain in their fields interspersed with crops (Gijsbers et al., 1994; Bayala et al., 2014). One of the few common tree species that favors crop production is *Faidherbia albida* (Del.) A. Chev., because of its reverse phenology. However, it is slow growing, typically has low densities of 30 trees ha⁻¹, and can take 4 to 6 years post-establishment before yields start to improve (Sanchez, 1995; Stoate and Jarju, 2008; Garrity et al., 2010). In recent years, more studies have focused on the CA potential of another component of parkland vegetation—native evergreen shrubs, and especially *Piliostigma reticulatum* and *Guiera senegalensis*. These shrubs are being studied as ecological and practical solutions for landscape remediation and the low yields of rainfed crops in the Sahel. Their advantages over trees are: higher densities, faster growth rates, limited competition for light, and prevention of erosion by entrapment of windblown sediment leading to higher fertility soils (Geiger and Manu, 1993; Wezel, 2000; Seghieri et al., 2005; Leenders et al., 2007; Lufafa et al., 2008).

P. reticulatum, specifically, extends from Senegal in the west to Sudan in the east and the Democratic Republic of Congo in the south (Hernandez et al., 2015). Research has shown that this shrub has a significant effect on the hydrology of soils within its canopy influence by increasing volumetric water capacity, minimizing drainage losses by capturing water not used by crops, performing hydraulic lift (HL), and using water from deep in the soil profile thereby not competing for water used by crops (Kizito et al., 2006, 2007, 2012). This species also enhances rhizosphere microbiology increasing microbial biomass and respiration, arbuscular mycorrhizal colonization in adjacent plants, the diversity and composition of bacterial and fungal species

(Diedhiouet al., 2009; Diedhiou-Sallet al., 2013; Hernandezet al., 2015). Furthermore, it promotes beneficial microorganisms, beneficial enzyme activity thereby increasing the rate of mineralization of nutrients for plant uptake, and overall biogeochemical cycling of phosphorus (P) and nitrogen (N) (Wezel et al., 2000; Dossa et al., 2008, 2013; Debenportet al., 2015; Diakhatéet al., 2016). *P. reticulatum* amplifies carbon (C) sequestration (Lufafaet al., 2008; Yelemou et al., 2013). Finally, in shrub-based cropping systems, pearl millet (*Pennisetum glaucum* (L.) R. Br.) and groundnut (*Arachis hypogaea* L.), yields are significantly increased in the presence of *P. reticulatum* (Geiger and Manu, 1993; Dossaet al., 2013; Debenportet al., 2015).

Both millet and groundnut are very important to livelihoods in the Sahel (Stoate and Jarju, 2008; Masonet al., 2015b). However, the long-term effects of *P. reticulatum* on their yields in addition to soil C and nutrient cycling have not been studied. Moreover, it is unknown whether the shrubs can maintain yields over fluctuating year-to-year rainfall typical of the Sahel. The main objective of this study, therefore, was to determine if an optimized *P. reticulatum* and millet/groundnut intercropping system with shrubs at high densities could sustain or increase yields over an 11-year period. Auxiliary objectives were to measure the long-term effects of *P. reticulatum* on C sequestration and nutrient cycling between soil, shrubs, and crops.

2. Materials and methods

2.1. Experimental Site

This long-term *P. reticulatum* intercropping experiment is located near Nioro-du-Rip, Senegal, West Africa, in the southern Peanut Basin (13°45'N, 15°47'W), within the Northern Sudanian climatic region (Sarret 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. The predominant shrub in this region is *P. reticulatum* with densities ranging from 134 to 288 shrubs ha⁻¹ (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 to 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). Air temperatures range from 20.0 to 35.7°C and the mean annual precipitation from 2011 to 2015 was 709 mm which fell primarily between July and September (Supplementary Fig. 1).

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. The experiment had a randomized complete block split-plot design with the presence or absence of shrubs as the main plot and fertilizer rate as the sub plot ($n=4$). Eight main plots, 46 X 4.5 m, were established in the winter of 2003 where half of them had all shrubs removed manually (–shrub plots) and the other half used the existing shrubs and in most cases increased the numbers in each plot to achieve a shrub density ranging from 667 to 1555 ha⁻¹ (+shrub plots). Within each main plot, 4 subplots, 10 X 4.5 m, were established with a 2-m gap between

subplots and a 3-m gap between main plots. Fourteen of the sixteen ⁺shrub subplots had 4 or 5 shrubs subplot⁻¹, randomly but evenly distributed, representing a fixed density of either 889 or 1111 shrubs ha⁻¹ and thus an average density of 1000 shrubs ha⁻¹ across all ⁺shrub plots. Data was collected from this experimental site for the years 2004 to 2007 and published by Dossa et al. (2013). The current study covers the years from 2011 to 2015. Other related studies that have been carried out at this site are Kizito et al. (2006, 2007, 2012) and Diakhaté et al. (2016).

During the summer of 2003, millet (var Souna 3) was planted in all plots and fertilized with 68.5 kg N, 15 kg P, and 15 kg K ha⁻¹. The following year groundnut (var 77-33) was planted. Subsequently, the same varieties of millet (odd years) and groundnut (even years) were planted at the site until the end of 2015. Shallow pre-planting tillage and other practices were typical of the dominant farmer practices in the region (Dossa et al., 2013). Crop planting occurred each June with groundnut plants 15 cm apart with 50 cm between rows, and millet was planted at densities of 10,000 plants ha⁻¹, 0.9 m X 0.9 m apart. During the cropping season, weeding was done by hand hoeing and with an animal-drawn shallow cultivator to a 5-cm depth. Beginning in 2004, the subplot fertilizer treatments were established. These were 0, 0.5, 1.0, or 1.5 times the recommended fertilizer rate for each crop. For groundnut, this was 9 kg N, 30 kg P, and 15 kg K ha⁻¹ manually applied as a 6-20-10 blend post-germination and incorporated by hand hoeing to a depth of 5 to 8 cm. For millet, the recommended fertilizer rate was 22.5 kg N, 15 kg P, and 15 kg K ha⁻¹ spread manually as a 15-15-15 blend and incorporated lightly by hoe at planting followed by a sidedressing of 46 kg N ha⁻¹ as urea in 23 kg increments broadcast at 2 and 4 wk post-planting.

Each year, before the rainy season started in May or June, the shrubs were coppiced and cut into 5 to 10-cm pieces before these residues were spread evenly over the ⁺shrub plots. This

stands in contrast to the current management of *P. reticulatum* in this region which consists of burning parts or all of the coppiced biomass prior to planting (Lahmar et al., 2012; Dossa et al., 2013). During the cropping season, shrubs were coppiced twice more per growing season and residues returned to soil surface. Shrubs regrew during the dry season when there was also no weeding of the plots. After millet grain yield was harvested, the remaining millet biomass was left on the soil surface, but groundnut residue, which is typically harvested to feed livestock (Dossa et al., 2013), was removed from the fields. This sequence of management was maintained from 2004 to 2015 except that the fertilizer subplots were not kept up from 2008 to 2010 when no measurements were made.

2.3. Crop yield, WUE, biomass, and plant sampling

In October following crop maturity, the inner two-thirds of each subplot was harvested. For groundnut, the entire plant was dug up from each subplot, followed by 4 to 5 days of sun drying, before pods were removed from the biomass and each fraction was weighed separately. Millet grain yield was accomplished by harvesting panicles that air dried to <10% water content followed by separation of millet seeds from the panicle. Water use efficiency (WUE) was calculated for both crops by dividing crop yield by annual rainfall—740, 900, 622, 720, 775, 964, 634, 513, and 658 mm in 2004, 2005, 2006, 2007, 2011, 2012, 2013, 2014, and 2015 respectively—to achieve kg yield ha⁻¹ mm⁻¹ rainfall. WUE was used to compare yields from 2004-2007 (published in Dossa et al., (2013)) with yields from 2011-2015. The aboveground millet biomass (leaves and stalks) was cut at the soil surface, weighed fresh, and a subsample of ~500 g was used to determine water content at 65°C. In 2015, representative samples of dried stems and leaves from each subplot were ground with a Wiley Mill to pass a 2-mm mesh and kept in sealed plastic bags for nutrient content analysis.

2.4. Aboveground shrub biomass and plant sampling

The fresh weight of aboveground shrub biomass was separated into leaf and stem components and recorded after each coppicing event. The shrub biomass was collected in late spring (first coppice) and during the cropping season (typically two times). Summing the biomass harvested over these two periods provided the annual shrub biomass yields. As with crop biomass fractions, a 500-g subsample of each component was used to determine moisture content. In 2015, representative fractions of dried stems and leaves from both shrub harvesting periods were ground and used to analyze nutrient contents.

2.5. Soil sampling

From 2012 to 2015, soil samples for chemical analyses were collected three times over the cropping season: 1) at planting but before fertilization (planting); 2) two months post-planting during the middle of crop growth (midseason), and; 3) at harvest. At each sampling, 10 soil cores (2.5 cm diameter and 0-10 cm depth) were randomly taken along diagonals within the inner two-thirds of each subplot. Soil samples were homogenized, air-dried, and sieved to pass a 2-mm sieve and a 200-g subsample kept in a sealed plastic bag at room temperature for further analysis.

2.6. Laboratory procedures

2.6.1. Soil carbon measurements

Total soil carbon was measured on a C-144 Carbon Analyzer (LECO Corp. St. Joseph, MI). Particulate organic matter carbon (POM-C) was determined on soils sampled at planting and harvest during 2012, 2013, and 2015, according to the methods of Cambardella and Elliott (1992). Briefly, 30-g soil samples were placed in 100 mL of a 5 g L⁻¹ sodium hexametaphosphate [Na(PO₃)₆] solution and dispersed by shaking for 16 h on a reciprocal shaker. The soil was then passed through a 53 µm sieve, rinsed, and the slurry passing through

the sieve was dried until constant weight was achieved. The samples were then analyzed for total C by combustion on the C-144 Analyzer. The difference between the C content of the slurry that passed through the 53 μm sieve and that of a duplicate undispersed soil was considered to be the POM-C $>53 \mu\text{m}$, whereas the C fraction of the dried slurry multiplied by the weight of the dried slurry was considered to be the C fraction $< 53 \mu\text{m}$, and the summed fraction corresponded to the total soil C content. Bulk densities of 1.49 and 1.47 g cm^{-3} in the $^{+}\text{shrub}$ and $^{-}\text{shrub}$ plots respectively (Roger Bayala, personal communication) were used to calculate kg C ha^{-1} to a 10-cm depth in $^{+}\text{shrub}$ and $^{-}\text{shrub}$ plots in 2015.

2.6.2. Soil nutrients

For 2014 and 2015 soil samples, plant macro nutrients: phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg), and sulfur (S); and micronutrients: manganese (Mn), iron (Fe), zinc (Zn), and copper (Cu) were extracted using a Mehlich 3 solution (ammonium-fluoride-EDTA) (Mehlich, 1984), followed by analysis on an ICP-OES 700 (Agilent Technologies, Santa Clara, CA) (USEPA, 2007). Total extractable inorganic nitrogen (N) in the form of ammonium (NH_4) and nitrate (NO_3) were analyzed on soil samples from 2014 to 2015. For the 2014 samples, NH_4 and NO_3 were extracted using 1 M KCl and analyzed colorimetrically (Dossa et al., 2013). For 2015 samples, a 2 M KCl extraction was performed (Maynard and Kalra, 1993), followed by automated colorimetry (USEPA, 1993a, USEPA, 1993b).

2.6.3. Plant nutrients

Ground plant tissue samples were prepared for elemental analysis by conducting an acid digestion (Havlin and Soltanpour, 1980). Shrub and millet leaves and stems were digested and analyzed separately but fractions were summed to calculate total nutrient uptake. Instrumental analysis for P, K, Ca, Mg, S, Mn, Fe, Zn, and Cu was conducted by ICP-OES 700 (Agilent

Technologies, Santa Clara, CA) according to USEPA method 6010C (USEPA 2007) in order to determine how much nutrients were returned to the soil in the plant biomass. Certified reference material (NIST 1573a) was used for evaluating method recovery of all nutrients. Average (10 reps) recovery was within 15% of the certified value for every element. Analysis of total N in plant material was performed on an Elemental Analyzer 1108 (Carlo Erba Instruments, Milano, Italy).

2.7. Statistical analysis

Data were checked for normality and homogeneity of variance assumptions. The PROC MIXED procedure in SAS (Version 9.4; SAS Institute, Cary, NC) was used for statistical analysis of the split-plot design data with year, presence or absence of shrubs, and fertilizer rate analyzed as fixed effects and blocks as a random effect. Yield, crop biomass, soil nutrients and C fractions were treated as repeated measures in time. Differences were considered significant at $P \leq 0.05$, and Tukey's honest significant difference test was used to separate significant effects by fertilizer treatment within each year. Fertilizer effect on *P. reticulatum* biomass and nutrient uptake was analyzed only in shrub plots with a one-way ANOVA as a randomized complete-block-design. Regression analysis was used to evaluate relationships between shrub biomass and carbon fractions with millet and groundnut yield, and also to examine rainfall with shrub biomass.

3. Results

3.1. Crop Yield

3.1.1. Millet

Between 2011 and 2015, millet grain yield averaged across fertilizer treatments ranged from 1606 to 1248 kg ha⁻¹ in the ⁺shrub plots ($P < 0.001$) compared to between 1236 and 894 kg

ha⁻¹ in the ⁻shrub plots (Table 1). A significant interaction between the effect of year*shrub($P=0.05$) highlighted the different yield trends in the different plots. Namely, without shrubs, there was a 28% stepwise yield decrease for 2011, 2013, and 2015 with 1236, 1016, and 894 kg ha⁻¹ respectively, whereas with shrubs, there was a decrease in millet yields between 2011 and 2013 (1606 to 1248 kg ha⁻¹) followed by an increase to 1344 kg ha⁻¹ in 2015.

The shrubs significantly increased yields over no-shrub treatments from 2011 to 2015 ($P=0.0023$). This contrasted with the results in Dossa et al. (2013) where the shrub effect did not significantly affect millet yields in 2005 and 2007. From 2011 to 2015, yields were 34% greater in ⁺shrub plots over ⁻shrub plots (averaged across fertilizer treatments) and 105% greater in ⁺shrub plots without fertilizer. From 2005 to 2007, the respective differences were only 15 and 14% greater in the ⁺shrub plots (Supplementary Table 1). At $P\leq 0.05$, the post hoc analysis showed that without fertilizer addition, yield was significantly greater in the ⁺shrub plots during 2013 and at every fertilizer level in 2015. However, at $P<0.1$ the shrub effect was significant with 0 and 0.5X fertilizer treatment in 2011 as well (Table 1).

The effect of fertilizer on yield was very significant ($P<0.0001$) and regression analysis showed that it was best fitted to a linear model (Supplementary Fig. 2) in both the ⁺shrub and ⁻shrub plots ($R^2=0.73$ and 0.83 respectively). There was no significant shrub*fertilizer rate interaction ($P=0.41$), and the difference between the linear equations describing fertilizer and yield relationships in the ⁺shrub and ⁻shrub plots (Supplementary Fig. 2) showed that on average there was 367 kg ha⁻¹ more yield with *P. reticulatum* at every fertilizer level.

From the start of the experiment in 2005 to the end in 2015, WUE in the ⁺shrub plots increased at the 0.5, 1, and 1.5X fertilizer rates by 26%, 37%, and 65% respectively and decreased slightly (5%) with no fertilizer (Fig. 1). In the ⁻shrub plots, the trends were different

with decreases of 38% and 6% at the 0 and 0.5X fertilizer rates respectively, a 5% increase at 1X, and no increase at 1.5X. Averaged across fertilizer treatments, *P. reticulatum* increased WUE by 36%, whereas there was a 4% WUE decrease in the $\bar{\text{shrub}}$ plots.

3.1.2. Groundnut

Groundnut yields varied by year ($P < 0.0001$) where rainfall was 964 mm in 2012 and 513 mm in 2014. In the $^{+}\text{shrub}$ plots, the yields averaged across fertilizer treatments were 1727 and 1382 kg ha⁻¹ in 2012 and 2014 respectively and 1687 and 1143 kg ha⁻¹ in the $\bar{\text{shrub}}$ plots (Table 1). Though yields were greater in the $^{+}\text{shrub}$ plots at the 0 and 1.5X fertilizer rates during 2012, the shrub effect was not significant. However, shrubs did increase yields in 2014 ($P = 0.0003$) and the post hoc analysis showed that this effect was significant at the 0X fertilizer rate (Table 1). The yield averaged across fertilizer treatments was 2 and 21% greater in the $^{+}\text{shrub}$ plots in 2012 and 2014 respectively, but 23 and 39% greater at the 0X fertilizer rate.

WUE averaged across fertilizer treatments in the $^{+}\text{shrub}$ plots increased by 75, 42, 30, and 27% at the 0, 0.5, 1, 1.5X fertilizer rates respectively from 2006 (2004 is not considered because a drought that year caused the crop to be reseeded [Dossa et al., 2013]) to the last groundnut year in 2014 (Fig. 1). However, in the $\bar{\text{shrub}}$ plots there was a 17 and 7% increase at the 0 and 0.5X fertilizer rates and a 12 and 17% decrease at the 1 and 1.5X fertilizer rates. Averaged across all fertilizer treatments, WUE increased in the $^{+}\text{shrub}$ plots by 43%, but decreased in the $\bar{\text{shrub}}$ plots by 3%. Fertilizer rate did not have a significant effect on groundnut yields ($P = 0.31$) (Supplementary Fig. 2), and in 2014, the yield in the $^{+}\text{shrub}$, 0X fertilizer plot was greater than yields from plots receiving fertilizer.

3.2. *Piliostigma reticulatum* biomass and nutrient uptake

P. reticulatum aboveground biomass yields were extremely variable during the 5 years of this study ranging from 1212 to 8187 kg ha⁻¹ averaged across fertilizer treatments (Fig. 2). Averaged across all fertilizer treatments and the years 2011 to 2015, the aboveground shrub biomass addition was 3.9 Mg ha⁻¹ yr⁻¹, and in the plots without fertilizer the addition was 4.2 Mg ha⁻¹. Regression analysis showed a strong positive relationship between shrub biomass from the first coppice and the biomass that grew during the growing season (Fig. 3). There was also a positive relationship between rainfall that fell in September and October of the preceding year and biomass from the first coppicing event of the following year ($R^2=0.46$), in addition to total biomass from the following year ($R^2=0.41$)(Fig. 3). Interestingly, the positive relationship between same-year rainfall and shrub biomass was only nearly significant ($R^2=0.39$)(data not shown). There was also a linear relationship between total shrub biomass from 2012 and 2014 and millet yields in 2013 and 2015 (Fig. 4). However, there was no relationship between same-year shrub biomass production and millet or groundnut yields (data not shown). Fertilizer did not significantly affect shrub biomass yields at either sampling or the yearly total, although fertilizer was nearly significant at the first coppice ($P=0.11$). In 2015, *P. reticulatum* aboveground shrub biomass (4.6 Mg ha⁻¹ averaged across all fertilizer treatments) that was incorporated into the soil added 1395 kg C, 35 kg N, 22 kg K, 61 kg Ca, 14 kg Mg, and <3 kg ha⁻¹ of the rest of the measured nutrients (Supplementary Fig. 3).

3.3. Crop biomass and millet nutrient uptake

Shrubs significantly increased groundnut biomass in 2014 at the 0, 1, and 1.5X fertilizer rates and millet biomass in 2015 at the 1 and 1.5X fertilizer rates (Table 2). The overall model showed a significant shrub effect on millet ($P=0.0051$) and groundnut ($P=0.017$) and there was a consistent trend of greater crop biomass in the plots with shrubs where only one fertilizer level in

2011 and 2012 produced less biomass in the ⁺shrub than the ⁻shrub plots. Consistent with grain yield, fertilizer had a strong effect on millet and groundnut biomass but the interaction between shrubs*fertilizer was not significant.

In 2015, there was no significant difference between the nutrient concentration (mg kg⁻¹) in millet plants from the plots with and without shrubs. However, when the nutrient concentration was multiplied by total millet biomass at the plot level (kg ha⁻¹), the overall model showed a significant shrub effect for C, N, P, K, Mg, S, Ca, Cu, and Fe. Nevertheless, the post hoc analysis indicated that the shrub effect did not vary based on fertilizer levels except for C uptake at the 1 and 1.5X fertilizer rate (Supplementary Table 2). Ranges for C and macronutrient uptake in millet aboveground biomass from the 0 fertilizer treatment in ⁻shrub and ⁺shrub plots respectively were: 455-821kg ha⁻¹ C, 15-30 kg ha⁻¹ N, 0.7-1.7 kg ha⁻¹ P, 10-17 kg ha⁻¹ K, 9-19 kg ha⁻¹ Ca, 8-16 kg ha⁻¹ Mg, and 0.9-2.3 kg ha⁻¹ S.

3.4. Soil carbon

The analysis of POM-C and C <53 μm showed that in the top 10 cm of soil, the smaller fraction predominated in 2012, 2013 and 2015 (Fig. 5). C <53 μm increased by 50% (2429 to 3645 mg kg⁻¹) in the ⁺shrub plots from 2012 to 2015 (C <53μm and Total C were not measured from 2004 to 2007.). Notably, however, C <53μm decreased by 22% in the ⁻shrub plots during those same years from 2332 to 1829 mg kg⁻¹. There was also a 12% increase in total C in the ⁺shrub plots (3284 to 3682 mg kg⁻¹) but a 23% decrease in the ⁻shrub plots (2853 to 2188 mg kg⁻¹). POM-C decreased in both plots and was only 37 and 359 mg kg⁻¹ at the end of the experiment. In addition to differences between inter-year variation in C levels from ⁺shrub and ⁻shrub plots, there was also intra-year variation between planting and harvest soil C levels. In 2013, ⁺shrub C <53 μm increased from 2017 mg kg⁻¹ at planting to 2178 mg kg⁻¹ at harvest and

from 2686 to 3645 mg kg⁻¹ in 2015 (data not shown). In contrast, there were decreases in the ⁻shrub plots from 1807 to 1783 mg kg⁻¹ in 2013 and from 1912 to 1829 mg kg⁻¹ in 2015. Total C followed the same intra-year trends.

Shrubs significantly increased Total C at harvest in all three years ($P=0.0018$) and the post hoc analysis showed that difference was significant ($P<0.04$) at all fertilizer levels in 2013 and 2015 (Fig. 5). The shrub effect was also significant for Total C at planting in 2013 and 2015 ($P<0.02$). For C<53 μ m, the effect of shrubs was significant at planting in all three years ($P=0.0091$) and at harvest sampling in 2013 and 2015 ($P<0.0001$). Tukey's showed that C<53 μ m was significantly greater at every fertilizer level at harvest 2015 and at 1.5X fertilizer at planting in 2012, 2013 and harvest 2013 as well. The shrubs had no positive effect on POM-C levels in any of the three sampling years, and fertilizer rate also did not affect either of the C fractions or the total.

The analysis of soil C to a depth of 10-cm showed that at harvest there was 2534 kg ha⁻¹ more C <53 μ m in the ⁺shrub plots with no fertilizer addition (5146 ± 754 SE compared to 2612 ± 354 kg ha⁻¹). For total C, the difference was 2092 kg more total C in the ⁺shrub plots (5238 ± 718 compared to 3146 ± 186 kg ha⁻¹). At planting, the difference between ⁺shrub and ⁻shrub plot C <53 μ m and total C was 1417 kg and 809 kg respectively. Regression analysis of carbon fractions on crop yields showed no relationship with groundnut or millet yields.

3.5. Soil Nutrients

Of the ten essential plant nutrients analyzed in 2014 and 2015, *P. reticulatum* significantly increased the extractable levels of five of the six macronutrients (inorganic N, K, Ca, Mg, S) and two of the micronutrients (Mn and Cu) for at least one sampling period in both years. The effect of year was significant on all nutrients, and the fertilizer effect was significant

on all nutrients except S and Cu. The most pronounced differences between soil nutrients from plots with and without shrubs was for Ca, K, and Mg where the post hoc analysis showed that levels were significantly greater in the ⁺shrub plots with no fertilizer addition at all three samplings in both years (Fig. 6). Moreover, for those three elements the differences were significant during at least one of the sampling periods in both years at the other fertilizer levels. For inorganic N, the post hoc analysis showed that the ⁺shrub treatment was significantly greater at 1X fertilizer for harvest 2015, for S as well in harvest 2014, for Mn at harvest 2014 and 2015. The differences were also significant at 1.5X for Mn and Cu at harvest 2015 and at 0X fertilizer for S at harvest 2014. Across all fertilizer treatments, the levels of Ca ranged from 121 to 244 mg kg⁻¹ with shrubs and from 74 to 149 mg kg⁻¹ without them. For K, the respective shrub and no shrub ranges were 15 to 47 and 9 to 23 mg kg⁻¹ and for Mg from 20 to 51 and 9 to 32 mg kg⁻¹. Table 3 presents the levels of the other nutrients (inorganic N, P, Mn, Fe, S, Cu and Zn) at harvest sampling in 2014 and 2015.

4. Discussion

4.1. P. reticulatum intercropping and drought resistance

In Sub-Saharan Africa, precipitation is the most limiting factor for crop yields (Bruinsma, 2003). Moreover, the frequency, duration and consequences of droughts related to climate change are expected to increase in West Africa (Sheffield and Wood, 2008; Dai, 2013; Xue et al., 2016). Especially for the Sudanian region of the Sahel where *P. reticulatum* predominates, Sultan et al. (2013) predicted that 89% of the time millet yields will decrease when there is a $\pm$ 20% variation in annual precipitation combined with a long-term 0 to 6°C temperature increase. Consequently, an effective conservation agriculture (CA) system must first and foremost be able to buffer crop yields against erratic rainfall.

To determine the potential of a CA system to buffer crops against drought requires long-term field studies that capture year-to-year variability in precipitation, that include dry years, and that ensure sufficient time for soils to respond to management. This study met these criteria, running from 2004 to 2015 with 9 cropping seasons and rainfall ranging from 513 to 954 mm. The most direct evidence for the ability of *P. reticulatum* to buffer against drought is rainfall water use efficiency (WUE) values. In the ⁺shrub plots, both millet and groundnut WUEs had a general increase over time whereas in the ⁻shrub plots, WUEs decreased. Furthermore, the effect of shrubs on WUE was especially evident during the last three years of the experiment when precipitation was 92 to 237 mm below the regional mean annual precipitation of 750 mm (Kizito et al., 2006). Thus, optimized *P. reticulatum* intercropping systems that have high shrub densities and return coppiced biomass to the soil surface would be expected to be a significant buffer against climate change, in part because of increased WUE for millet and groundnut.

The increased WUE in ⁺shrub compared to ⁻shrub plots also translated to pronounced differences in true yield especially in the treatments without fertilizer during all five years from 2011 to 2015. At this site, variability kept Tukey's test from showing more significant differences by fertilizer treatment when we set the significance level at $P \leq 0.05$ as presented in Tables 1 and 2. However, large yield variability is characteristic of the Sahel (Therond et al., 2011) where rainfall sustains crops, soils have low fertility, and external inputs are rare. Nonetheless, in this study, mean yield (averaged over fertilizer rates) differences were still significant in all millet cropping years and with groundnut in 2014. Despite the somewhat high variability of the yields, we suggest that the large percentage differences between presence and absence of shrubs are more important for assessing the yield impact of the *P. reticulatum* system

than P values which are a function of the data and might have been significant at $P \leq 0.05$ had one more replicate been added to each treatment.

4.2. *P. reticulatum* intercropping and soil quality

While precipitation is a major climatic limitation in the Sahel, organic matter input is the most limiting management factor (Bationo and Buerkert, 2001; Lahmar et al., 2012) because it controls soil organic C (SOC) which in turn impacts yields (Roose and Barthès, 2001; Bationo et al., 2007; Lal, 2010). Therefore, a beneficial CA practice must not only buffer against limited soil water but also increase SOC. The average annual addition of C from the coppiced *P. reticulatum* biomass was $>1 \text{ Mg C ha}^{-1}$ and resulted in a significant increase both in C $< 53 \mu\text{m}$ and total C fractions from 2012 to 2015, whereas there were decreases in the $^{-}$ shrub plots in those same years. Thus, a millet-groundnut rotation which returned millet residue to the soil every other year but had no other organic inputs from either shrub above or belowground inputs was not able to prevent SOC losses. Similarly in Niger, there were no significant SOC increases in a 16-year continuous cropping system with similarly-textured soils (92% sand) and annual millet biomass additions of 2700 kg ha^{-1} (Adams et al., 2016). This emphasizes the importance of *P. reticulatum* in these sandy agroecosystems and a management system of coppicing, followed by spreading the residue mulch over the surface for remediating and preventing degradation of sandy soils.

In addition to SOC, enhanced nutrient availability is particularly important in the Sahel which has some of the oldest and most weathered soils in the world with low inherent fertility in the top soil (Lahmar, 2012). In this study, significantly higher levels of macronutrients in both measurement years and during all sampling periods in the $^{+}$ shrub plots without fertilizer suggests a consistent, sustained *P. reticulatum* improvement of soil quality. These results are also

consistent with reviews by Sinare and Gordon (2015) and Bayala et al. (2014), who reported that various trees and shrubs have positive effects on soil nutrients. Negative nutrient balances (greater losses than additions to the system) are typical in the Sahel (Bationo et al., 2007). Our results, however, indicate that even if yearly millet biomass were removed from the ⁺shrub plots without fertilizer, the nutrients in the aboveground shrub biomass would still be able to provide a positive nutrient balance. Moreover, since *P. reticulatum* residues decompose quickly with up to 80% of stem and 70% of leaf tissue broken down within 8 months (Diack et al. 2000; Diedhiou-Sall et al., 2013), this is a potential mechanism for the positive linear relationship between the preceding year's shrub biomass and the succeeding year's millet yield. Nutrients from this organic input were mineralized and the improved soil quality contributed to higher crop yield.

4.3. *P. reticulatum* intercropping and C sequestration

Agricultural production accounts for 15-25% of global anthropogenic greenhouse gas emissions (Vermeulen et al., 2012). Nonetheless, there is a strong link between soil C sequestration and food security (Lal, 2004) which makes climate smart agricultural systems that can increase SOC especially important for food security in the Sahel (Lipper et al., 2014). Agroforestry systems have been shown to sequester C in West Africa (Bayala et al., 2007; Lufafa et al., 2008; Takimoto et al., 2008;). However, other long-term studies that practiced continuous cultivation in sandy soils of the Sahel reported that CA practices did not sequester C (Subbarao et al., 2000; Yamoah et al., 2002). Our long-term investigation confirmed that continuous *P. reticulatum* intercropping significantly sequestered C in a sandy soil over an 11-year period. First, C < 53 μ m was the predominant C fraction in these soils and comprised nearly 100% of the total in the ⁺shrub plots by the end of 2015. That fraction is considered to be the protected C pool (Six et al., 2000; Kong et al., 2005). In addition, by 2015, the 2 Mg ha⁻¹ more C

<53 μm in the ⁺shrub plots was merely to a depth of 10 cm suggesting that the full C sequestration potential from shrubs is much greater if SOC were measured throughout the profile explored by shrub roots. Finally, C <53 μm continued to increase from 2012 to 2015 in the ⁺shrub plots, implying that this sandy soil had not yet reached its full C sequestration capacity. This conclusion is further supported by Aune and Lal (1997) who estimated that 1.1% SOC was the maximum limit that could be obtained in most tropical soils, which is well above the approximately 0.35% SOC levels in the ⁺shrub plots after 11 years of shrub-intercropping.

4.4. Mechanisms for increased yields and WUE with *P. reticulatum*

Competition between woody species and crops has been widely reported in the Sahel and limits the advantage of some agroforestry systems (Bazié et al., 2012; Bayala et al., 2015). However, this was not the case for *P. reticulatum*. In fact, greater in-season regrowth of shrub biomass corresponded with greater millet and groundnut yields from 2011 to 2015 and also from 2004 to 2007 (Dossa et al., 2013). An important question, then, is why *P. reticulatum* does not compete with crops for water and nutrients and furthermore why yields and WUE are increased near shrubs. The results of this study suggest several mechanisms for this lack of competition.

First, *P. reticulatum* is improving soil quality and nutrient availability (Section 4.2) which could offset or overcome any competition for water and nutrients between shrubs and crops. Nutrient competition would be reduced if shrubs made more nutrients available to crops from above and belowground additions. Even if the effect of woody vegetation on soil fertility is merely a redistribution of nutrients rather than a true gain to the system as discussed in Bayala et al. (2015), these data nonetheless showed that a *P. reticulatum* intercropping system could prevent losses of nutrients which occurred in the ⁻shrub plots without shrub inputs. The higher SOC in the ⁺shrub plots no doubt also improves soil structure and consequently root growth and

nutrient uptake by the crop. This effect is consistent with other studies showing that improved soil quality increased yields in the West African Sahel (Sanou et al., 2010; Bargués et al., 2014; Bayala et al., 2015).

Several mechanisms can be attributed to limited competition for water between *P. reticulatum* and crops. One set of mechanisms is related to improved retention and availability of water from a soils perspective with the presence of *P. reticulatum*. The improvement in soil structure from higher SOC in the ⁺shrub plots increases water infiltration and storage, thus making more water available to the whole system. Moreover, the return of shrub biomass to the soil surface reduces evaporation, conserves water, and improves yield (Trail et al., 2016). The improvement in WUE especially during years with below-average rainfall was partially attributable to hydraulic lift (HL) which Kizito et al. (2012) did establish for *P. reticulatum*. HL is the movement of water from wet subsoil to drier surface soil by roots at night when photosynthesis stops and can improve the growth of plants next to the HL donor in water-limiting environments (Sun et al., 2014; Pang et al., 2016).

Another factor is the difference in spatial water use between *P. reticulatum* and crops. 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. Here we suggest another mechanism that explains lack of competition between *P. reticulatum* and crops—a temporal offset in the times when shrubs and crop take up water which is based on three lines of evidence: 1) the strong positive correlation between shrub biomass from the 1st coppicing event and shrub biomass produced during the growing season; 2) the relationship between rainfall from the end of the preceding year and the succeeding year's shrub biomass—meaning that shrubs are getting water for subsequent growth at a time (late season) when crop water requirements are

decreasing; and 3) no relationship between in-season shrub biomass production and millet or groundnut yields.

While the relationship between biomass from the 1st coppice and biomass during the growing season could be due to decomposition and release of nutrients from the 1st coppice, the lack of relationship between in-season shrub biomass and crop yield suggests that increased nutrients were not the main cause of the relationship. Moreover, the shrubs did not significantly respond to the fertilizer treatments which is further evidence that fertility was not the main cause of differences. Root turnover and nutrient mineralization deeper in the soil profile were not examined and could have contributed to inter-year differences in shrub biomass and lack of competition between shrubs and crops. Also, shrub biomass did track yearly rainfall, but the relationship between yearly rainfall and within-season biomass production was not as strong as the relationship between late season rainfall from the previous year and shrub biomass from the following year. Thus, there is strong evidence that the crops are largely using water during the early to mid-growing seasons, whereas the shrubs are using water from the late rainy season when crops are decreasing their demand for water—a remarkable ecological mechanism of two species having off-setting temporal use of rainfall.

4.5. Management considerations for farmers and future research of P. reticulatum intercropping

Although this study showed a dramatic effect of elevated *P. reticulatum* density on soils and crop productivity, it is unknown whether the optimal density is greater or less than 1000 shrubs ha⁻¹. In the Nioro-du-Rip region where this research was conducted, Lufafa et al. (2008) reported 134 to 288 *P. reticulatum* shrubs ha⁻¹ which means our study had densities 3 to 4 times higher than what is currently found across cropped fields. In this experiment, one shrub occupied 10 m², and much of the positive influence of shrubs is attributable both to the shrub

residue mulch spread across the surface and to belowground root turnover. Importantly, this study showed that the *P. reticulatum* intercropping system at 1000 shrubs ha⁻¹ could improve yields and soil quality at the field scale and not just directly beneath the shrub canopy (Bayala et al., 2015). Frequently there is high variability of soil nutrients at a very localized scale across the Sahel (Manlay et al., 2002; Voortman et al., 2004), and more studies are needed to determine the density where shrubs can still improve yields at the field scale but not be outweighed by shrub-crop competition.

Another consideration in developing scaling campaigns for adoption of optimized shrub intercropping systems is the amount of time needed to incur measurable benefits. The shrub effect on yield was not significant in 2005 and 2007 (Dossa et al., 2013) but was significant from 2011-2015 which showed that it took >4 years to obtain consistently elevated yields when shifting to an optimized *P. reticulatum* system. Thus, the time and labor investment to establish this intercropping system might not see a return in yield increase over the short term. Importantly, however, farmers in Burkina Faso recognize the importance of *P. reticulatum* not only for soil fertility improvement but also its economic value for construction, animal forage, and medicinal uses (Zoundi et al., 1996; Yelemou et al., 2007, 2009, 2013, 2015). These ecosystem services, therefore, are an important component of a successful agroforestry system (Sinare and Gordon, 2015), and a farmer who relies heavily on livestock production might value the significant increased groundnut biomass for animal feed from shrub-based intercropping. More participatory studies are needed to determine economic tradeoffs and overall farmer attitudes to wide-scale adoption of a high-density *P. reticulatum* intercropping system that coppices and returns biomass to the soils rather than the current practice of low shrub density and burning parts of all of the coppiced shrub biomass (Lahmar et al., 2012; Dossa et al., 2013).

Parkland agroforestry systems of the Sahel are typically composed of multiple tree species in farmers' fields (Bayala et al., 2015). Kizito et al. (2006) and Dossa et al. (2013) mention eight other woody species scattered throughout interspaces between *P. reticulatum* in the fields adjacent to this research station. There is potentially a synergistic effect of trees and shrubs, but this is entirely uninvestigated. Future experiments, therefore, should study the effect of mixtures of woody species—for example *P. reticulatum* with *Combretum glutinosum* and *F. albida*—on crop yields to determine whether a mixed tree and shrub system might have the same results as a homogeneous shrub stand. The final challenge for *P. reticulatum* implementation is related to climate variability. Reports of the overall re-greening of the Sahel (Kaptué et al., 2015) conflict with other reports indicating declines in both alpha and beta diversity of woody species across the Sahel (Gonzalez et al., 2012; Brandt et al., 2017). This suggests that climate effects on woody vegetation are extremely localized, and that rainfall affects the distribution of *P. reticulatum* (Yelemou et al., 2015). More studies are needed that examine the morphology and physiology of shrub and crop interactions and specifically intra-season variation due to rainfall. These studies should also examine the *P. reticulatum* intercropping system not only in Senegal but also in the other countries of the West African Sahel to determine the range of this species.

5. Conclusions

The simplicity, elegance, and potential of *P. reticulatum* to meet the current challenges of food insecurity, climate change, and land degradation is clearly evident from the results of this long-term study. First and foremost, the shrubs consistently increased groundnut and millet yields over plots without them between 2011 and 2015 indicating that the shrub intercropping system would increase food security both in adequate rainfall years and during drought periods. Furthermore, with respect to groundnut cultivation when shrubs were present, there was little

further yield benefit from fertilizer addition which is an advantage for subsistence farmers who have limited resources to purchase this input.

The mechanisms behind the yield advantage were increased soil quality and WUE dynamics. Moreover, the *P. reticulatum* intercropping system is also important because it provides significant ecosystem services. First, it can simultaneously increase yield and C sequestration which is an advantage rarely seen in sandy soil agroecosystems. Thus, increasing the plant density of *P. reticulatum* along with non-thermal management of coppiced biomass in farmers' fields would be an effective, long term strategy to capture CO₂ emissions and store them in soil. It also increased biomass yields which are important for livestock forage.

Questions still remain about optimal shrub densities and interactions with tree species for further yield improvement. However, the outcomes of this study combined with supporting reports on specific components of the *P. reticulatum* intercropping system (Wezel, 2000; Diack et al., 2000; Kizito et al., 2007, 2008, 2012; Lufafa et al., 2008; Dossa et al., 2008; Diedhiou-Sall et al., 2013; Yelemou et al., 2009, 2013; Diakhaté et al., 2016) provide a solid foundation to launch farmer participatory projects to pilot test and demonstrate this optimized *P. reticulatum* system throughout the Sahel. The advantages of *P. reticulatum* are that the shrub is a local resource that is dominant across the Sahel, requires very little maintenance, and has multiple uses: medicinal, animal husbandry, and construction. The combined beneficial uses make this shrub-intercropping system an implementable solution for improving the livelihoods of subsistence farmers and increasing C storage to buffer against the threat of climate change.

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841 **Table 1. Effect of the presence or absence of *P. reticulatum* and fertilizer rate on crop yields over five growing seasons at the**
842 **long-term research station in Nioro, Senegal.**

	2011 Millet			2012 Groundnut			2013 Millet			2014 Groundnut			2015 Millet		
	⁺ Shrub	⁻ Shrub	Mean	⁺ Shrub	⁻ Shrub	Mean	⁺ Shrub	⁻ Shrub	Mean	⁺ Shrub	⁻ Shrub	Mean	⁺ Shrub	⁻ Shrub	Mean
<u>Fertilizer rate</u>	<u>kg ha⁻¹</u>														
0	886	499	693	1672	1354	1513	749	315	532	1526	1096	1311	592	298	445
0.5X	1429	1047	1238	1713	1763	1738	1194	847	1021	1380	1204	1292	1198	738	968
1X	1806	1457	1632	1710	1837	1774	1375	1402	1389	1237	1137	1187	1565	1151	1358
1.5X	2302	1939	2121	1812	1794	1803	1675	1502	1589	1384	1135	1260	2022	1388	1705
Mean	1606	1236	1421	1727	1687	1707	1248	1016	1132	1382	1143	1263	1344	894	1119
<i>P</i> values using Tukey's test*															
0	0.078			NS			0.039			0.017			0.18		
0.5X	0.085			NS			0.15			0.76			0.0077		
1X	0.14			NS			1			0.98			0.019		
1.5X	0.11			NS			0.85			0.37			0.0002		
Mean	<0.0001			NS			0.0013			0.0003			<0.0001		

* *Tukey's test was used to separate differences between pairs of ⁺shrub and ⁻shrub values within the same fertilizer rate and year.*

845 **Table 2. Aboveground crop biomass in the presence or absence of *P. reticulatum* under varying fertilizer rates over five**
846 **growing seasons at Nioro, Senegal.**

Fertilizer rate	2011		2012		2013		2014		2015	
	Millet		Groundnut		Millet		Groundnut		Millet	
	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub
	kg ha ⁻¹									
0	1495	999	1963	1821	1491	833	2179	1358	1996	1094
0.5X	2653	2020	2144	2134	2391	1784	1957	1628	3076	2115
1X	3203	3292	2274	2290	2912	2806	2111	1620	3958	2897
1.5X	4533	3909	2569	2222	3597	3077	1989	1564	4914	3467
Mean	2971	2555	2238	2117	2598	2125	2059	1543	3486	2393
<i>P</i> values using Tukey's test*										
0	0.72		NS		0.25		0.0001		0.19	
0.5X	0.44		NS		0.33		0.30		0.14	
1X	1		NS		1		0.03		0.080	
1.5X	0.46		NS		0.52		0.085		0.0072	
Mean	0.012		NS		0.0017		<0.0001		<0.0001	

847

848 * *Tukey's test was used to separate differences between pairs of ⁺shrub and ⁻shrub values within the same fertilizer rate and year.*

849 **Table 3. Extractable soil nutrients (other than Ca, K, and Mg) in the presence or absence of *P. reticulatum* under varying**
850 **fertilizer rates at harvest 2014 and 2015.**

	Total Inorganic N		P		S		Mn		Fe		Cu		Zn	
	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub	⁺ Shrub	⁻ Shrub
<u>Fertilizer rate</u>														
<u>2014</u>	mg kg ⁻¹													
0	33a‡	25.5a	11.5a	11.7a	5.1a	4.1b	66.2a	66.5a	24.8a	28.7a	0.32a	0.32a	0.68a	0.21a
0.5X	36.4a	31a	16a	14.7a	4.4a	4.1a	62.8a	68.1a	27.2a	30.2a	0.31a	0.32a	0.31a	0.28a
1X	32.9a	29.4a	20.8a	19.8a	4.5a	3.8a	64.9a	58.2a	29.7a	30.1a	0.32a	0.3a	0.29a	0.28a
1.5X	34.6a	28.7a	31.8a	26.8a	4.7a	3.6b	63.4a	50.2a	31.7a	30.1a	0.33a	0.27a	0.42a	0.25a
Mean	34.2a	28.7b	20.0a	18.3a	4.7a	3.9b	64.3a	60.8a	28.4a	29.8a	0.32a	0.30a	0.43a	0.26a
<u>2015</u>														
0	29.6a	22.5a	6.9a	8.2a	3.8a	2.5a	46.8a	44.6a	13.3a	16.1a	0.31a	0.23b	1.3a	0.68a
0.5X	27.3a	22.6a	10a	10.5a	3.4a	3.1a	46.6a	46.6a	17.5a	18.1a	0.26a	0.24a	0.36a	0.6a
1X	36.1a	21.3b	15.2a	15.6a	4a	2.4a	50.9a	40.3a	17.9a	18.8a	0.27a	0.25a	1.7a	1a
1.5X	31.5a	25.9a	17.7a	22.5a	3.9a	3.7a	47.2a	31.9b	18.7a	18.8a	0.3a	0.22b	0.75a	0.66a
Mean	31.1a	23.1b	12.5a	14.2a	3.8a	2.9b	47.9a	40.9b	16.9a	18.0a	0.29a	0.24b	1.0a	0.74a

851 ‡ Pairs of ⁺shrub and ⁻shrub values within a fertilizer rate and year followed by the same letter are not statistically different at
852 P<0.05.

853
854

Figure captions

Fig. 1. WUE millet (a) and groundnut (b) yield from 2004 to 2015 in ⁺shrub and ⁻shrub plots for the 4 fertilizer treatments. Data from 2004 to 2007 adapted from Dossa et al. (2013). Bars are SEM for the 5 cropping years.

Fig. 2. *P. reticulatum* biomass yields from a) the first coppice, b) the growing season, and c) the annual total across the four fertilizer levels from 2011 to 2015. The connected circles above the years represent a) the rainfall that fell during September and October of the preceding year, and b) the rainfall that fell during the concurrent growing season. Bars represent SEM.

Fig. 3. Regressions showing relationships between: a) shrub biomass from the first coppice and biomass during the growing season, b) rainfall from the preceding September and October and shrub biomass from the 1st coppice of the following year, and c) rainfall from the preceding Sept. and Oct. and total biomass from the following year. Bars represent SEM.

Fig. 4. Regressions showing relationships between: a) shrub biomass during the growing season (excluding the first coppice) in 2012 and 2014 at 0X fertilizer and millet yield from the same plots in 2013 and 2015, and b) the total biomass (including first coppice) from 2012 and 2014 with millet yield from 2013 and 2015.

Fig. 5. Total C and distribution of the POM-C, and C <53 μ m fractions in ⁺shrub and ⁻shrub plots over 4 fertilizer rates at harvest in 2012, 2013, and 2015. Pairs of ⁺shrub and ⁻shrub total C values within a fertilizer rate followed by the same letter are not statistically different.

Fig. 6. Soil extractable Ca, K, and Mg at planting, midseason, and harvest in the ⁺shrub and ⁻shrub plots at 0X fertilizer during the 2014 (groundnut) and 2015 (millet) cropping seasons. Asterisks represent significant differences within sampling date at $P < 0.05$. Bars represent SEM.

A)

B)

Total C (POM-C + <53 μ m) mg kg⁻¹