Crop Productivity and Nutrient Dynamics in a Shrub (*Guiera senegalensis*)–Based Farming System of the Sahel

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ABSTRACT

The indigenous shrub, *Guiera senegalensis*, coexists with crops to varying degrees in farmers' fields throughout the Sahel, with little known about its biophysical and ecological interactions with soils and crops. Therefore, the objectives were to determine the effect of the presence or absence of shrubs under varying rates of fertilizer on: (i) crop growth and yield, and (ii) soil nutrient dynamics. An experiment from 2004 to 2007 was conducted in northern Senegal where *G. senegalensis* dominates that had a split-plot factorial design. The presence or absence of *G. senegalensis* was the main plot and fertilizer rate (0, 0.5, 1 or 1.5 times the recommended N–P–K rate) was the subplot in a peanut (*Arachis hypogaea* L.)–pearl millet [*Pennisetum glaucum* (L.) R. Br.] rotation. Averaging over fertilizer rate showed that *G. senegalensis* had significantly greater crop biomass and yields than no shrub plots ($P < 0.05$) for all 4 yr. This crop yield response was related to improved nutrient availability (significantly greater for crop N and P uptake in the presence than absence of shrubs in zero fertilizer plots), higher soil quality (elevated particulate organic matter (POM) with shrubs, and a significant correlation of POM with millet yield). Lysimeters below the crop rooting zone had inorganic N levels that were not significantly affected by shrubs compared to no shrub plots, which was attributed to high variability. Combining the ecological potential to restore degraded landscapes with the agronomic benefits demonstrated here, shows that optimized *G. senegalensis*–crop systems should be further investigated in farmers' fields throughout the Sahel.

Agricultural systems of semiarid sub-Saharan Africa are vulnerable because of ongoing anthropogenic soil degradation and declining soil productivity (Lal, 2002). This trend is partly explained by increased pressure from growing rural populations on agricultural lands, overexploitation of woody resources (Tilander et al., 1995), inability of resource-limited farmers to replenish the soil of nutrients removed by crops (Buresh and Tian, 1998; Breman et al., 2001; Mafongoya et al., 2006a), and soil organic matter lost in cultivation. In these nutrient and water-limited ecosystems, a reasonable combination of organic and inorganic amendments are necessary to develop sustainable options for agriculture and to optimize crop productivity (Sanchez et al., 1997; Badiane et al., 2000; Nyamangara et al., 2003; Akinnifesi et al., 2007; Tittonell et al., 2008).

Efficient use of nutrients and water is critical in sandy Sahelian soils. Recovery of inorganic fertilizers applied in cropped fields is generally low. Low recovery rates <30% have been reported for N, a major element limiting productivity in tropical soils, as a result of intense leaching of NO_3–N below the rooting zones of crops (Nyamangara et al., 2003; Mafongoya et al., 2006a). Although P is less mobile than N in soils, high application rates in sandy and low P-fixing soils such as those of Sub Saharan Africa (Dossa et al., 2008) may result in P leaching down the soil profile. Management practices that can increase organic inputs to soils in semiarid cropping systems are needed to improve nutrient and water use efficiencies and optimize crop productivity.

Agroforestry systems that combine trees or shrubs with crops can potentially provide organic inputs and improve nutrient recovery and use efficiency (Mafongoya et al., 2006b). Mechanisms include: nutrient recovery from subsoil layers not explored by the crop that are deposited on the surface layer through litter input and root turnover; reduced nutrient loss; (Young, 1989; Gathumbi et al., 2004); and improved soil physical, chemical and biological soil properties (Buresh and Tian, 1998). Hartemink et al. (2000) in Kenya showed that *Sesbania sesban* (a shrub) during fallow periods, can retrieve considerable subsoil inorganic N (mainly as NO_3) in highly weathered Alfisol and Oxisol soils. This N was shown to be effectively recycled for subsequent crops.

In Senegal and throughout the drier northern Sahel, *Guiera senegalensis*, a shrub, is found to varying degrees as an integral

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Abbreviations: POM, particulate organic matter.

part of the cropping systems in farmers' fields. Unlike trees, which are vulnerable to overexploitation (Tilander et al., 1995; Wezel, 2000), this shrub is adapted to yearly coppicing and can establish relatively quickly (Seghieri et al., 2005).

Traditional management of this shrub includes annual spring coppicing and burning of residues before cultivation of row crops. Kizito et al. (2006) reported that *G. senegalensis* has the majority of its root biomass in the 0.2 to 0.5 m depth and preferentially utilizes water below 0.9 m and does not compete with adjacent crops for water. An additional characteristic of *G. senegalensis* is that it creates islands of fertility with higher C and N contents of soil beneath than outside the canopy (Dossa et al., 2010). This spatial heterogeneity of nutrient distribution created by shrubs may influence plant-nutrient dynamics and ultimately crop productivity.

There is no in-depth research on the interactions of *G. senegalensis* with crop productivity and nutrient cycling in the Sahel. Wezel (2000) in farmers' fields of Niger found millet [*Pennisetum glaucum* (L.) R. Br.] had greater yields due to the presence and litter residue of *G. senegalensis*. Whereas Kizito et al. (2006) had a nonsignificant ($P < 0.05$) yield increase of millet in the presence of shrubs (non-optimized system where coppiced shrub residue was burned and had low density of 240 shrubs ha^{-1}) over adjacent bare soil. Other studies showed the potential of *P. reticulatum* (another local shrub in the Sahel found in farmers' fields) residues can be used as soil organic amendments (Diack et al., 2000; Iyamuremye et al., 2000) that can be decomposed by soil microorganisms and release nutrients. However, these studies (Diack et al., 2000; Iyamuremye et al., 2000) give only indirect evidence for improving soils for crop production.

There are no studies that have compared crop yields of an optimized shrub system (nonthermal residue management with high shrub density) with a nonshrub system at field scales. Therefore, the objectives of this study were to investigate the presence or absence of *G. senegalensis* at varying rates of fertilizer on a peanut–pearl millet rotation in relation to (i) crop yield; (ii) N and P uptake of shrubs and crops; and (iii) soil nutrient dynamics.

MATERIALS AND METHODS

Study Sites

The research was done in the Peanut Basin of Senegal in West Africa, which is semiarid and has most of the precipitation distributed from July to October, generally as intense short-duration showers. Millet and peanut (*Arachis hypogaea* L.) are the two major crops.

The experimental site (Keur Matar Arame) is in the northern region of the Peanut Basin (14°45' N, 16°51' W, and 43 m above sea level), with mean annual precipitation of 450 mm and temperatures ranging from 20°C in December–January to 33°C in April–June. Cumulative annual rainfall at the site was 300, 560, 303, and 578 mm in 2004, 2005, 2006, and 2007, respectively. The rainfall pattern over the study period is shown in Fig. 1.

The soil (Rubic arenosol) (FAO, 2006), known locally as Dior had 95% sand, mainly originates from aeolian deposits and has no distinct horizonation in the top 1 m layer (Badiane et al., 2000). The top soil (0–10 cm) has organic matter and total N contents of 0.35 and 0.02% respectively, P content of 95 mg kg^{-1}, and mean pH (water) of 5.5. In this region *G. senegalensis* is the dominant shrub in farmers' fields with an

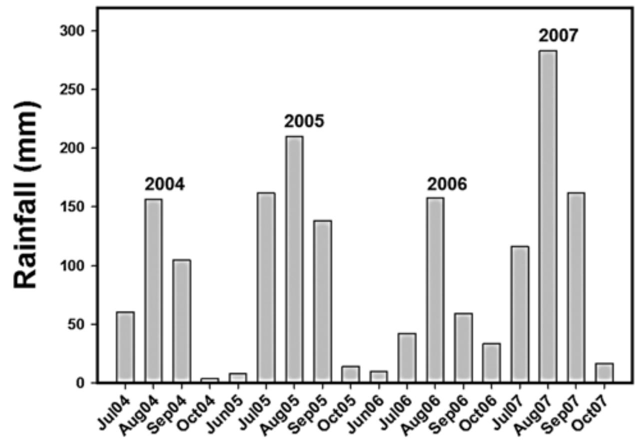

Fig. 1. Distribution of rainfall at Keur Matar, Senegal, from 2004 to 2007.

average density of 240 ha^{-1} (Kizito et al., 2006; Lufafa et al., 2008b). Herbaceous vegetation in the interspace between shrub stands consists of annuals dominated by *Alysicarpus ovalifolius* (Schum.) J. Leonard, *Cenchrus biflorus* Roxb., *Dactyloctenium aegyptium* (L.) Willd., *Eragrostis pilosa* (L.) P. Beauv., and *Merremia tridentata* (L.) Hall. (Dossa et al., 2010).

Experimental Design

A field of approximately 0.5 ha with pre-existing shrubs was selected that had been under local farmer management for at least the last 50 yr. The site had been cropped continuously with a peanut–millet rotation before the experiment (but left fallow for 3 yr before initiating the experiment). The experimental design was a split-plot with presence or absence of shrub as the main plot and fertilizer rate as the subplot with four replicates.

The main plots were established in the winter (dry season) of 2003 by manually removing existing shrub from no shrub plots and for shrub plots most plots had 9 to 11 shrubs per plot (except for four plots that had lower stand levels and had seedlings transplanted to achieve similar density as the other shrub plots in 2003) for a stand density of 1500 to 1833 shrubs ha^{-1}. Shrubs were randomly but relatively evenly distributed. The following summer, millet was planted on all plots and fertilized with 68.5 kg N, 15 kg P, and 15 kg K ha^{-1} to allow plots to equilibrate for 1 yr before initiation of the experiments. Main plot sizes were 46 by 6 m and subplot sizes were 10 by 6 m. There was a 2-m gap between adjacent plots and 3-m gap between blocks. Following the dominant farmer practices in the region, all plots had a crop rotation of peanut (*Arachis hypogaea* variety 55-437) and millet (*Pennissetum glaucum* variety Souna 3) over the experimental period from 2004 to 2007.

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} that was manually broadcast after peanut germination followed by hand hoeing incorporation to a depth of 5 to 8 cm. The recommended fertilizer rate for millet was 22.5 kg N, 15 kg P and 15 kg K ha^{-1} applied at planting followed by 46 kg N ha^{-1} as urea (split of 23 kg 2 wk and 4 wk after planting). Fertilizer applied at planting was incorporated whereas the subsequent N applications were broadcast.

In 2004, peanut was planted 15 cm apart with a distance of 50 cm between rows in early August. During the second growing season in 2005, in July millet was planted at 1 by 1 m distance with four to six seeds per hole. After germination, the plants were thinned to one to two plants per hole. Weeding was done by a shallow cultivator to a 5-cm depth, drawn by animal traction. In the fallow period there was no weeding and shrubs were allowed to regrow. Shrub plots were coppiced in April and during the cropping season until crops were near maturity in October or November (this followed standard farmer practices in terms of coppicing except that the residues were not burned).

Aboveground crop biomass, however, was managed according to farmers' practices where millet was left in plots but peanut was removed. This peanut–millet sequence was repeated with peanut in 2006 and millet in the 2007 following the management practices described above.

Soil Sampling and Solution Collection

Soil samples for chemical analyses were taken from each subplot before fertilizer treatments and monthly after fertilizer application. For each sampling date, 10 soil cores (2.5 cm diam.) per subplot were randomly taken to a 10-cm depth along the diagonals within the inner two-thirds of each subplot. The cores were homogenized, air-dried, and sieved to pass a 2-mm sieve and a 200- g sample was kept in a sealed plastic bag under room temperature for further chemical analyses.

Collection of soil solutions was done with lysimeters that were installed at 55- to 60-cm depth in subplots receiving zero or the highest rate of fertilizer (0 and 1.5 times the recommended fertilizer rate, respectively) in presence or absence of shrubs. The lysimeters consisted of a PVC tube (~2.5 cm diam.) fitted with a porous ceramic cup at one end; the other end was sealed with a rubber stopper. Before installation, the ceramic cups were washed with deionized water and the first collected sample was discarded to allow the cups to equilibrate with the soil.

Each subplot with shrubs had one lysimeter placed in the middle of the canopy and one in the outer edge of the canopy of two representative shrubs (based on canopy height and diameter). In the subplots without shrubs, the porous cups were randomly placed, one between two plants in a row and the other one, between two rows in the middle point formed by four plants. After installing the lysimeter before planting of the crop in 2004, a slurry of clay (approximately 2:1 water/clay mixture) was placed at the soil surface around the base of the lysimeter to avoid possible artifacts caused by water infiltration along the tubes during rainfall events. The lysimeters, as described above were placed in two of the four blocks of the major experimental design. From June to August in 2004 and from June to October in 2005, soil solution was sampled every 2 wk. Before each sampling, a suction of 54 cm Hg was applied to the lysimeters using a hand-held vacuum pump and soil water samples were collected using a 50-mL syringe. The collected soil solution samples were composited per replicate, transported in the laboratory and added two to three drops of chloroform and frozen until they were analyzed.

Crop Yield Assessment and Plant Sampling

The inner two-thirds of each subplot were harvested for both crops. In the case of peanut the entire plant was mechanically removed from the plots, sun-dried for 4 to 5 d, and pods separated from biomass. Millet grain yield was determined by harvesting millet ears from the entire harvested area. Ears were sun-dried that resulted in water content of <10% and shelled to yield dry millet grain per subplot. When significant damage of granivorous bird was noticed, millet grain yield in the affected subplots was corrected by using a shelling ratio (weight of grain)/(weight of empty ear) derived from unaffected millet plants from the same plot to estimate the true yield of damaged ears. Estimated grain weight of bird damaged ears and grain weight of intact, undamaged ears was summed to determine yield grain weight of each plot affected by bird damage.

The aboveground biomass of millet (leaf + stalk) was cut at the soil surface and fresh weight was recorded. Composite samples of approximately 500 g were taken for water content determination after drying at 65°C to a constant weight.

Coppiced shrub aboveground biomass, at the beginning of each cropping season and during the crop growing season was sorted into leaf and stem components and fresh weight was taken of each component. For each biomass component, a composite sample of approximately 500 g was taken for water content determination by drying at 65°C to a constant weight. Representative samples for the different plant tissues were ground with a Wiley mill through a 2 mm mesh and kept in sealed plastic bag for subsequent chemical analyses. The remainder of the leaf and stem (chopped into ~5 to 10 cm lengths) residue was returned to the soil (in the spring it was lightly incorporated just before planting and during the growing season was placed on the soil surface).

Laboratory Procedures

Particulate organic matter determination was performed as described by Cambardella and Elliott (1992) on 0 to 10 cm soils sampled at end of season in October 2007. Dry soil samples of 30 g (<2 mm) were dispersed by shaking for 16 h on a reciprocal shaker in 100 mL of 5 g L^{-1} sodium hexametaphosphate-$NaPO_3$ solution. After dispersion, the soil was passed through a 53 µm sieve, rinsed several times with deionized water and the slurry passing through the sieve was collected and dried in a forced-air oven at 50°C until constant weight. The dried sample was ground with a mortar and pestle and analyzed for total C by combustion on a LECO WR-12 C autoanalyzer (LECO Corp., St. Joseph, MO). The difference between C of the slurry and that of the duplicate nondispersed soil was considered to be the C retained on the 53 µm sieve.

Soil inorganic P was extracted by the $NaHCO_3 + NH_4F$ method buffered to pH 8.5 (Dabin, 1967). Soil ammonium N and nitrate N was extracted with 1 M KCl and analyzed by the salicylate-nitroprusside, and the hydrazine-sulfanilamide methods, respectively (Mulvaney, 1996) after filtration through a glass fiber filter. For total N and P, plant tissues and soil solution samples were digested using a modified Kjeldahl Li_2SO_4–H_2SO_4 procedure (Parkinson and Allen, 1975). Nitrogen in the digests was determined by the salicylate-nitroprusside procedure (Mulvaney, 1996). Phosphorus in extracts, soil solution samples, and digests were analyzed for orthophosphate by the molybdenum blue colorimetric method (Murphy and Riley, 1962) after pH adjustment using a 5 M NaOH solution when necessary. In the ($NaHCO_3$ + NH_4F)-P determination (Dabin, 1967), interference of F^- with color formation was prevented using a 0.8 M H_3BO_3 solution.

Statistical Analysis

Statistical analysis of the data was performed using the PROC MIXED subroutine (SAS Institute, 1999) for a split-plot design. Yield and biomass data for peanut in 2004 and 2006, or for millet in 2005 and 2007, were treated as repeated measures in time and analyzed as a split-split-plot, with year as the whole plot factor. Contrasts were used to assess the shrub vs. no shrub effect at different fertilizer levels. Additionally, fertilizer rate was treated as a quantitative factor and a direct regression approach (PROC MIXED) was used to examine linear or quadratic fit of fertilizer rate on crop yield, crop biomass, or crop nutrient uptake. Fertilizer effect on *G. senegalensis* biomass and N, P in biomass was restricted to the main plots with shrubs and analyzed as a randomized-complete-block design (PROC GLM).

Shrub biomass data was also normalized to a per shrub basis (total biomass or biomass nutrient uptake as kg nutrient per plot/number of shrubs per plot) and biomass and associated N and P were regressed on N and P rates using PROC REG (SAS Institute, 1999). For soil data, within each year, soil extractable N and P for the different sampling dates were analyzed as repeated measures in time (SAS Institute, 1999). Mean separation for significant effects was performed with Tukey's Honestly Significant Difference test.

RESULTS AND DISCUSSION

Grain Yield

Peanut response to fertilizer in presence or absence of shrubs varied with years ($P < 0.0001$), with higher yield in 2006 than in 2004 (502 and 133 kg ha^{-1}, respectively, values averaged across shrub/no shrub and fertilizer rates). For millet, the year effect was not significant ($P > 0.20$) with mean grain yield of 258 and 330 kg ha^{-1} for 2005 and 2007, respectively.

The ANOVA showed that both shrub and fertilizer rates were significant ($P < 0.05$) for yields of both crops in all years. Plots with shrubs had significantly higher yields than plots without shrubs when averaging across fertilizer rates (Table 1). This was a consistent and significant yield response of shrub over no shrub treatments at all levels of fertilizer for all years, except in 2006 at the 1.0 recommended fertilizer rate. The yield differential was most dramatic in 2007 on millet where it was difficult to maintain a stand after germination on the nonshrub plots without fertilizer. As shown in Table 1, with no fertilizer added, the no shrub plots yielded 6 kg ha^{-1} compared to shrub plots that had 197 kg ha^{-1} for 2007. At the highest fertilizer rate the plus shrub plots yielded 622 kg ha^{-1} compared to 174 kg ha^{-1} which was a 250% yield increase because of shrub presence.

Regression analysis showed that fertilizer effect on millet yield was best fitted to a linear model ($P < 0.002$) in 2005 and 2007. The shrub × fertilizer rate interaction was not significant ($P > 0.24$), indicating little evidence that the linear fertilizer trend differed between shrub and no shrub cropping systems. For peanut yields in 2004 and 2006 a linear fit of fertilizer rate was not significant ($P > 0.4$). However, in 2006 peanut yield data showed a significant quadratic response to fertilizer rate ($P = 0.02$). For both years, shrub × fertilizer interaction was significant ($P < 0.03$).

The linear response of millet grain yield to fertilizer is very common in Sahelian agroecosystems (Bationo et al., 1993) and would be expected on the sandy soils of our study. While yield levels of 2005 and 2007 are within the expected yield range (Dancette, 1978; van Duivenbooden and Cissé, 1993; Diangar et al., 2004), values of peanut in 2004 and 2006 fell below long-term averages partly due to a rainfall deficit (M. Sene, personal communication, 2007).

An interesting outcome is that 3 out of the 4 yr, there was a significant increase ($P < 0.05$) in yield from 1.0 to 1.5 fertilizer rates in the presence of the shrub compared to the nonshrub treatment (Table 1). This would suggest that the

Table 1. Crop yield as affected by presence of shrub (*G. senegalensis*) and fertilizer rate during 4 growing seasons in Senegal.

	2004 (*Arachis hypogaea*)			2005 (*Pennissetum glaucum*)			2006 (*Arachis hypogaea*)			2007 (*Pennissetum glaucum*)		
	Shrub	No shrub	Mean	Shrub	No shrub	Mean	Shrub	No shrub	Mean	Shrub	No shrub	Mean
Fertilizer rate						kg ha^{-1}						
0	190a†	78b	134	218a	11a	164	384a	273b	329	197a	6b	101
0.5	135a	103a	119	359a	148b	253	542a	449b	495	403a	85b	244
1	153a	116a	134	422a	278b	350	556a	579a	567	378a	200b	289
1.5	203a	91b	147	605a	503a	554	708a	532b	620	622a	174b	398
Mean	170a	97b		400a	260b		547a	458b		400a	116b	
Trend analysis over fertilizer rate‡												
	Shrub	No shrub	Combined	Shrub	No shrub	Combined	Shrub	No shrub	Combined	Shrub	No shrub	Combined
Linear	ns	ns	ns	***	***	**	***	***	ns	**	ns	***
Quadratic	ns	ns	ns	ns	ns	ns	ns	***	*	ns	ns	ns
Shrub × linear	-§	-	ns	-	-	ns	-	-	ns	-	-	ns
Shrub × quadratic	-	-	*	-	-	ns	-	-	*	-	-	ns

† Each pair of no-shrub and shrub means within a fertilizer rate (or averaged over fertilizer rate) and year followed by the same letter is not statistically different at $P < 0.05$.

‡ Examination of linear or quadratic effects of fertilizer at $P < 0.05$ (*), $P < 0.01$ (**), and $P < 0.001$ (***) or not significant (ns).

§ Not applicable.

recommended rate of fertilizer is not adequate in the presence of shrubs which may reflect the greater yield potential in the presence of shrubs. This is illustrated by the quadratic equation for peanut yield in 2006 in the absence of shrubs, which was $Y = 266 + 514x - 222x^2$. Solving the derivative of this equation for zero results in an optimum fertilizer rate of 1.15 times the recommended rate. In presence of shrub however, the optimum falls outside the range of values used in this experiment, which suggests that rates higher than 1.5 times the recommended fertilizer rate would be needed for optimal crop yield. An alternative explanation could be that shrubs are taking up fertilizer nutrients but this is unlikely during the growing season because shrub sprouts are immediately coppiced so that there was little biomass production.

The current recommended fertilizer rates were largely derived from experiments done at research stations in plots without shrubs (M. Sene, personal communication, 2007). This is important because even though farmers do not manage shrubs actively, the shrubs to varying degrees are commonly found in farmers' fields throughout the Sahel. This would suggest a new research initiative is needed in the Sahel on fertilizer rates for crops when grown in the presence of shrubs.

The fertilizer effect on crop yield was more apparent in 2005 and 2007 when water was not limiting crop growth (M. Sene, personal communication, 2007). The higher crop yield with shrubs than without, is consistent with a report in Niger of higher yields of millet adjacent to coppiced or uncopicced *G. senegalensis* over millet outside the influence of *G. senegalensis* (Wezel, 2000). This improved yield in the presence of shrubs could have resulted from several mechanisms. When no fertilizer was applied, the higher crop yield in plots with shrubs may have been due to better plant nutrition, which follows the idea of "islands of fertility" created by woody shrub species in semiarid environments (West, 1991; Kieft et al., 1998; Wezel et al.,2000).

The positive crop response in the presence of shrubs even in a very dry year (2004) suggests that shrubs were not significantly competing with the crop for water. This was indeed found by Kizito et al. (2007) who showed no competition for water between shrubs and millet and a significantly higher soil moisture profile in millet–shrub intercrop plots than in sole millet plots on the same experimental plots we used. Additionally, *G. senegalensis* could have been providing water by performing hydraulic lift (Richards and Caldwell, 1987) of water from the wet subsoil to the dry surface soil as shown by Kizito et al. (2012).

From the above discussion the presence of *G. senegalensis* appears to minimize nutrient and water stress. Interestingly, when nutrient stress (1.5 fertilizer rate) and water stress (high rainfall years 2005 and 2007) are removed or significantly reduced, our results still show a yield response on millet due to *G. senegalensis*. This would suggest there might be other factors beyond nutrients and water relations that enable shrubs to improve growth of associated crops which is further discussed below.

The crop response in the minus shrub plots suggests there is a legacy effect of shrubs. Evidence for this was shown in 2007, where, after 4 yr of cropping without shrubs and fertilizer, there was near crop failure because of poor stand establishment. In contrast, shrub plots with no fertilizer had respectable millet stands (this was not due to any mulching effect as coppiced material was incorporated before planting). This would suggest that fields that do not have *G. senegalensis* in the sandy soils of northern Senegal may become so degraded that crop establishment becomes difficult. It should be kept in mind that nonshrub plots did have some shrubs in the plots that were removed a year before we started the study. It may well be that there were some residual effects of these shrubs that after they were removed in 2003, but after 4 yr, these effects had been lost, as evidenced by the poor crop stand in 2007.

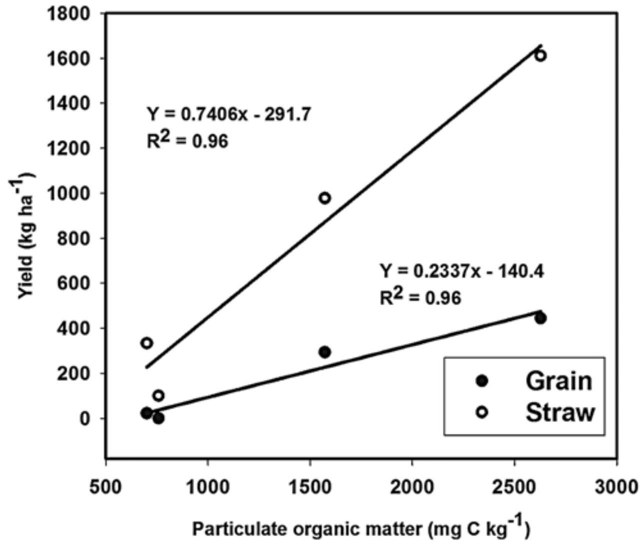

Fig. 2. Relationship between particulate organic matter (POM) content of soil (0–10 cm) and millet grain and stover yields at Keur Matar, Senegal. Data are from 2007 season.

Particulate Organic Matter

The evidence from particulate organic C (POM) measurements (Fig. 2) would suggest that *G. senegalensis* has improved the quality of soils or inhibited soil organic matter degradation. The POM is related to soil quality because it is mostly composed of carbohydrates originating from fresh plant material (Wander and Nissen, 2004) that can improve soil structure (Jastrow, 1996). It promotes aggregation by: acting as an aggregate, being a nucleus for macroaggregate formation (Bayer et al., 2002; Diekow et al., 2005), and also by stimulating microbial activity that drives aggregation. The *G. senegalensis* plots had significantly ($P < 0.05$) higher (1650 mg POM-C kg^{-1} soil) and twice as much POM than the minus shrub plots (755 mg POM-C kg^{-1} soil) (data not shown). The positive effects of POM were further reinforced by a significant relationship between POM and millet yield (Fig. 2).

By increasing POM, shrubs promote a better structured soil with greater porosity that can improve water efficiency by increasing water holding capacity and enable roots to better explore the soil for resources. These results are supported by Dossa et al. (2010) who found greater organic C levels beneath than outside the shrub canopies and rhizopheres.

Crop Biomass and Nitrogen and Phosphorus Uptake

Crop biomass in 2004 was affected by locust invasion and therefore, only the portion of biomass without leaves was reported and no nutrient uptake is reported. There was a significant year effect on peanut biomass ($P < 0.002$), with

Table 2. Aboveground crop biomass and nutrient uptake in the presence or absence of *G. senegalensis* under varying rates of fertilizer over three growing seasons at Keur Matar, Senegal.

	2004 (*Arachis hypogaea*)						2005 (*Pennisetum glaucum*)						2007 (*Pennisetum glaucum*)					
	Mass		Nitrogen		Phosphorus		Mass		Nitrogen		Phosphorus		Mass		Nitrogen		Phosphorus	
	Shrub	No shrub	Shrub	No Shrub	Shrub	No Shrub	Shrub	No shrub	Shrub	No shrub	Shrub	No shrub	Shrub	No shrub	Shrub	No shrub	Shrub	No shrub
Fertilizer rate	kg ha^{-1}																	
0	424a†	328b	na‡	na	na	na	893a	638b	9.1a	5.5b	4.7a	2.8b	844a	189b	12.1a	4.3b	3.5a	1.1b
0.5	583a	409b	na	na	na	na	1767a	1083b	8.4a	6.4a	5.2a	3.7a	1767a	951b	21.9a	15.9b	6.2a	2.3b
1	462a	480a	na	na	na	na	1815a	1653a	11.9a	7.9b	5.5a	3.9a	1892a	1411b	25.5b	39.5a	4.8a	5.6a
1.5	600a	495b	na	na	na	na	3340a	2122b	21.9a	15.1b	8.7a	5.1b	2669a	1472b	35.5a	30.5a	6.1a	3.6b
Mean	517a	428b	na	na	na	na	1954a	1374b	12.8a	8.7b	6.0a	3.9b	1793a	1005b	23.8a	22.5a	5.1a	3.1b
Trend analysis over fertilizer rate§																		
Linear	*		na		na		*		**		na		***		ns		ns	
Quadratic	ns		na		na		ns		ns		ns		ns		*		*	
Shrub × linear	ns		na		na		ns		ns		ns		ns		ns		ns	
Shrub × quadratic	ns		na		na		ns		ns		ns		ns		*		*	

† Each pair of values between Shrub and No shrub treatments for Mass, N uptake or P uptake within a year and fertilizer rate (or averaged over fertilizer rate), followed by the same letter is not significantly different at $P < 0.05$.

‡ Data not available.

§ Examination of linear or quadratic effects of fertilizer at $P < 0.05$ (*), $P < 0.01$ (**), or $P < 0.001$ (***) or not significant (ns).

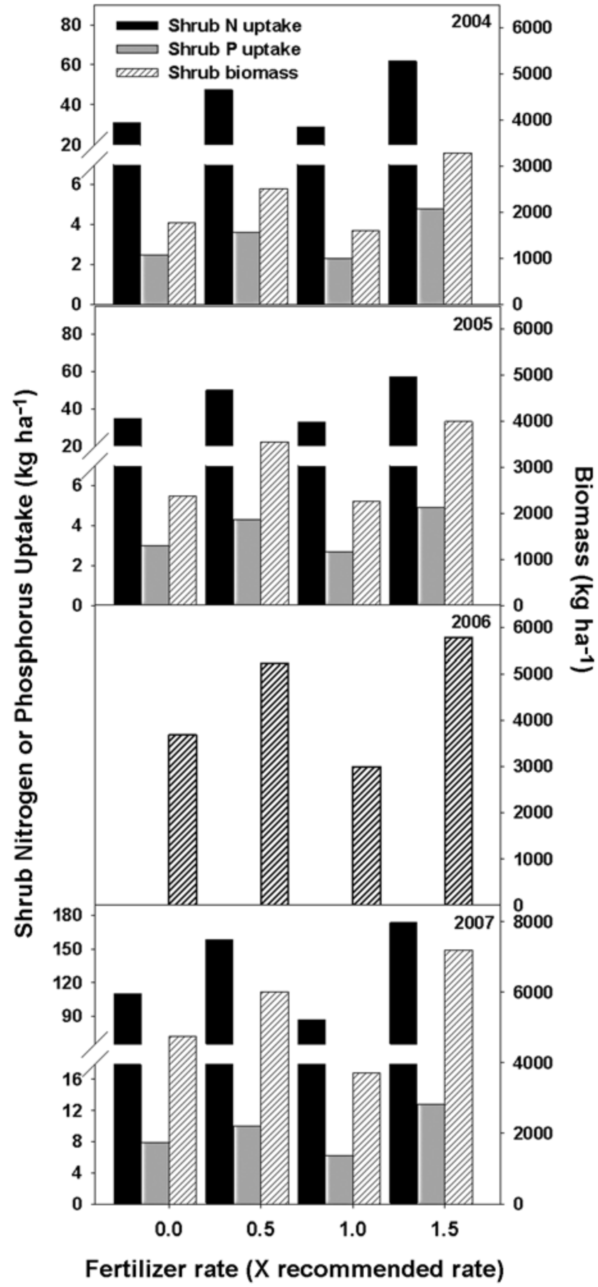

Fig. 3. Biomass and nutrient uptake of *G. senegalensis* under varying rates of fertilizer applied to crops at Keur Matar, Senegal.

higher yields in 2006 than in 2004 (651 and 472 kg ha^{-1} respectively, when averaging across all treatments). The year effect was not significant for millet biomass ($P > 0.15$).

Presence of shrubs and application of fertilizer significantly increased crop biomass and biomass N and P contents (Table 2). Crop biomass in the presence of the shrub at every fertilizer rate over all 3 yr was consistently higher than in plots without shrubs, except in 2004 at 1.0 fertilizer rate (Table 2). In 2005, millet aboveground biomass ranged from 638 to 3340 kg ha^{-1}; showed a shrub effect ($P = 0.005$); and when regressed on fertilizer rates had a significant linear fit ($P < 0.0001$). However, for millet aboveground biomass, the shrub × fertilizer interaction was not significant ($P = 0.35$). The magnitude of the difference between shrubs and no shrubs treatments was greatest at the highest fertilizer rate (Table 2).

Interestingly, even in the absence of fertilizer, the presence of *G. senegalensis* resulted in a ~40% increase in millet biomass.

Crop N and P uptake was similar to crop biomass with a consistent shrub response across all fertilizer rates over the 3 yr these parameters were measured, except at rate 1.0 in 2007 (Table 2). Nitrogen and P uptake in millet biomass was lowest in unfertilized sole millet plots (5.5 kg N and 2.8 kg P ha^{-1}) and highest in millet–shrub intercropped plots receiving the highest rate of fertilizer (21.9 kg N and 8.7 kg P ha^{-1}) (Table 2). The shrub effect on biomass N uptake was significant ($P < 0.006$) and fertilizer effect on crop nutrient uptake had a significant linear fit ($P < 0.0008$). There was no fertilizer × shrub interaction ($P > 0.68$) for biomass N and P.

During the 2007 season, the same trend was observed as in 2005 but generally more N was taken up in a slightly lower amount of crop biomass, which we attribute to the inverse relationship between biomass nutrient concentration (data not shown) and total biomass. The biomass–fertilizer rate relationship was linear ($P < 0.0001$). For crop biomass there was a significant shrub effect ($P = 0.005$) but no significant shrub × fertilizer interaction ($P = 0.34$). Conversely, the crop biomass N uptake-fertilizer rate relationship did fit a quadratic model at a $P < 0.09$. Crop N uptake had a shrub × fertilizer interaction at $P < 0.09$.

The ANOVA of year to year data within shrub plots showed that millet biomass production in the zero fertilizer treatment was not significantly ($P > 0.05$) different between 2005 and 2007, at 893 and 844 kg ha^{-1}, respectively. Whereas in the absence of shrubs, millet biomass was dramatically and significantly ($P < 0.001$) lower in 2007 than in 2005 at 189 and 638 kg ha^{-1}, respectively. This emphasizes the vital role of shrubs in maintaining productivity of sandy low-C soils of semiarid ecosystems and gives support to our suggestion in the previous section that Sahelian soils degrade rapidly when shrubs are removed from fields.

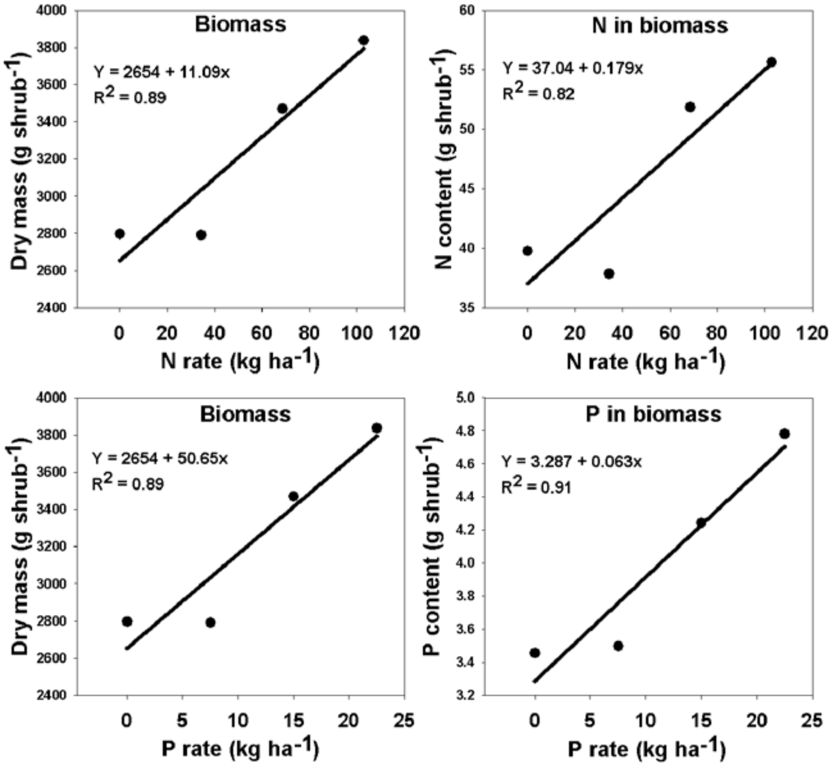

Fig. 4. Relationship between applied fertilizer, biomass production, and biomass N and P uptake of *G. senegalensis* at Keur Matar, Senegal in 2005 season when calculated on a per shrub basis.

Guiera senegalensis Biomass, and Nitrogen and Phosphorus Uptake

Shrub biomass as well as N and P in shrub biomass showed no apparent response to fertilizer ($P > 0.05$) for the 2004, 2005, or 2007 seasons (Fig. 3). Shrub biomass yield increased over the years (data not shown). This overall response may be due to the use of fertilizer at the experimental site and/or possibly it could be due to the fact that some seedlings, planted the year before the experiment to meet the target density, have started producing a noticeable biomass.

The shrub fertilizer relationship was most likely confounded by the variability in shrub size and shrub number per subplot at the beginning of the experiment. When shrub biomass and nutrient uptake were calculated on a per shrub basis (total biomass or biomass nutrient uptake/number of shrubs/plot), there was a quasi-linear and positive relationship between shrub biomass and N and P in biomass with increasing fertilizer rates for *G. senegalensis* (Fig. 4). This suggests that, *G. senegalensis* may be acting as a scavenger of residual fertilizer nutrients and could therefore improve nutrient use and uptake efficiency by recycling nutrients in its biomass.

Extractable Soil Nitrogen and Phosphorus

Extractable nitrate and ammonium were pooled because their levels in soils were quite low. In 2004, extractable inorganic N of soils decreased throughout the growing season but exhibited a rise in concentration at the end of the growing season (Fig. 5). Soil inorganic N content was not affected by fertilizer rate, but was significantly higher ($P < 0.05$) in plots with shrubs than in sole millet plots, supporting the idea that these shrubs are creating islands of fertility.

In 2005, inorganic N of soils dropped rapidly to lower levels than in 2004 and showed significant shrub and fertilizer rate effects ($P < 0.05$) (Fig. 5). The soils showed a rise in N content at the end of season (Fig. 5) which reflects decreasing rainfall and hence decreasing leaching toward the end of the season.

The lower levels of extractable soil inorganic N early in the growing season may reflect microbial and crop uptake of N as well as greater losses of soluble N with leaching or runoff with the high rainfall at that time of the year. Comparing the low N levels in 2005 when rainfall was above average with the higher levels of inorganic N in the dry year of 2004 supports this conclusion. These results would suggest that N applications should be split and not all applied at planting to reduce potential N leaching and to improve N use efficiency.

Extractable soil P in 2004 steadily increased in soils at Keur Matar (Fig. 6) over the season. Extractable P content of

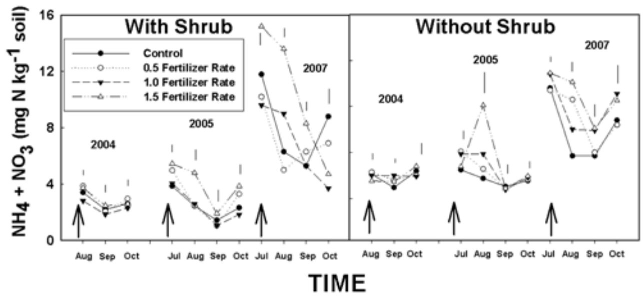

Fig. 5. Inorganic N dynamics in soils as affected by presence of shrubs and fertilizer rate at Keur Matar, Senegal in 2004, 2005, and 2007 seasons. Vertical bars represent Tukey's Honestly Significant Difference at *P* < 0.05. Arrows show time of fertilizer application.

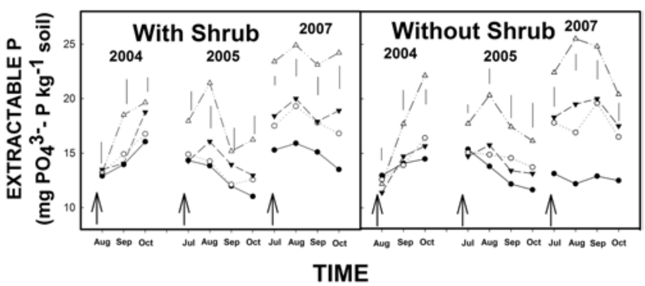

Fig. 6. Extractable P in soils as affected by presence of shrubs and fertilizer rate at Keur Matar, Senegal in 2004, 2005, and 2007 seasons. Vertical bars represent Tukey's Honestly Significant Difference at *P* < 0.05. Arrows show time of fertilizer application.

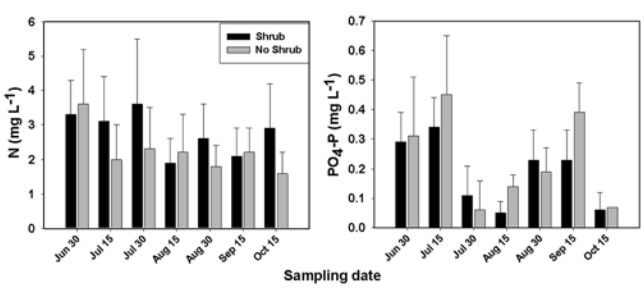

Fig. 7. Temporal variation of (left) N and (right) P concentration of soil leachates in millet field in presence and absence of shrubs at Keur Matar, Senegal. Data are from 2005 growing season. Bars represent standard error on the mean.

soils was not affected by presence of shrubs but significantly increased ($P < 0.01$) with increasing P fertilizer rates. In 2005, soil P, initially increased up to August and thereafter decreased until the end of the growing season (Fig. 6). In 2007, soil extractable P increased significantly ($P < 0.001$) with fertilizer rate. Extractable P was significantly higher in shrub over no shrub plots. At the end of the 4-yr study extractable P was higher than those of previous years (Fig. 6) suggesting P was accumulating after 4 yr of fertilization and that the presences of shrubs may be conserving and/or promoting release of plant available P forms.

The increase in soil extractable N and P contents at the end of the growing season in the dry year of 2004 may partly be attributed to release of nutrients from microbial death (Brookes et al., 1982). Similarly, Magid and Nielsen (1992) reported a negative correlation between inorganic P and soil moisture due to physical changes in soils rather than biological turnover. Indeed, dehydration of soils subsequent to air-drying has been shown to affect P desorption properties of soils (Barrow and Shaw, 1980; Haynes and Swift, 1985). Such drying and wetting processes likely occurred toward the end of the rainy season.

The leachate solution levels of N and P are shown for 2005 in Fig. 7 as a typical example of all the years. Although the actual amounts did vary somewhat between years, lysimeter nutrient concentrations were relatively low and the temporal and fertilizer rate patterns were very similar across all years. Nitrogen concentration in soil leachates showed temporal variation and was generally highest in early samplings (Fig. 7), confirming the dynamic nature of inorganic N in these sandy soils. There was no significant effect of *G. senegalensis* on N leachate concentration and there was no consistent trend over sampling dates on shrub vs. nonshrub effects (Fig. 7). It seems logical that shrubs likely are conserving inorganic N that would otherwise be leached out of the rooting zones of crops in these sandy soils but lysimeter data does not confirm this.

In contrast to N, P concentration in soil leachates had higher variability and although generally higher in early season samplings, did not show a significant sampling date effect or a significant shrub effect (Fig. 7). This result partly reflects the less dynamic nature of phosphate in soils and likely the strong controls of soil chemistry on phosphate.

CONCLUSIONS AND PERSPECTIVES

The presence of shrubs significantly affected peanut and millet productivity and inorganic N content of soils throughout the 4-yr study. In both dry and wet years, crop yield was higher with shrubs than without shrubs and for the most part this yield response was consistent from zero to the 1.5 fertilizer rate levels. This result is particularly pertinent for the northern Sahel region with sandy, often degraded soil because, as shown in other studies, *G. senegalensis* not only provides ecological benefits to landscapes (Lufafa et al., 2008ab) and soils (Diedhiou et al., 2009; Dossa et al., 2010) but also as our study showed, dramatically increased crop productivity (in some cases 250%). Furthermore, *G. senegalensis* is a locally available resource and it provided crop yield responses even with low or no fertilizer applications, making this system well suited for subsistence, low in-put farmers.

Under optimal rainfall conditions, fertilizer applied at 1.5 times the recommended rate was effective in increasing crop yield, and crop and shrub biomass over the 1.0 fertilizer rate. This suggests the current recommended fertilizer rates are too low when shrubs are present. Generally, inorganic N content of soils decreased rapidly to very low levels near the end of the growing season, which may explain the poor N recovery by crops in sandy soils. In these soils, split applications of N fertilizer should be recommended to reduce nutrient loss and improve nutrient use efficiency.

Our results provide very convincing evidence that shrubs, as managed in the present study, are not competitive with crops, and indeed significantly improved crop yield, total biomass, and uptake of N and P for millet. Such an attribute is important with respect to nutrient cycling and land use sustainability of semiarid ecosystems. The results suggest that shrubs should be recognized as an important component of cropping systems in the Sahel, particularly in the more arid zones. Further research should investigate biogeochemical and microbiological interactions between shrubs and crop rhizosphere and quantify the resistance of *G. senegalensis* to agricultural disturbance in maintaining soil resource islands. Although agronomic studies on optimal shrub–crop densities and spatial distributions are needed, our results provide a foundation for scaling up and testing optimized shrub–crop systems in farmers' fields across the Sahel.

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