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THE INFLUENCE OF NATIVE WOODY SPECIES, COMBRETUM GLUTINOSUM AND PILIOSTIGMA RETICULATUM, ON SOIL FERTILITY IN DIALACOTO, SENEGAL

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THE INFLUENCE OF NATIVE WOODY SPECIES,
COMBRETUM GLUTINOSUM AND *PILIOSTIGMA RETICULATUM*,
ON SOIL FERTILITY IN DIALACOTO, SENEGAL

By

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Abstract

In the low-fertility soils of Senegal, West Africa, management of woody species in agricultural fields has the potential to improve soil fertility and crop production. However, optimal species for this purpose have not been clearly defined. Thus, the objective of this study was to evaluate the potential for two native woody species, *Combretum glutinosum* and *Piliostigma reticulatum*, to improve soil fertility. Soil samples were collected from beneath tree crowns of *P. reticulatum* and *C. glutinosum* and compared with fertilizer-amended and non-amended soil from adjacent open fields in a bioassay experiment. Two common crops, millet *(Pennisetum glaucum)* and maize *(Zea mays)*, were grown in soil samples and crop growth and biomass production were measured as indicators of relative soil fertility. Maize biomass and growth parameters were greater in soils from beneath *P. reticulatum* as well as in field soil amended with chemical fertilizer. However, most parameters of millet growth and biomass did not respond to differences in soil chemistry. Chemical analyses determined that most soil fertility indices were greater in soil from beneath *P. reticulatum* and *C. glutinosum* than in adjacent open fields. Net nitrogen mineralization however was only significantly greater in soils from beneath *P. reticulatum*. While the study results indicate that both woody species can positively influence soil fertility, *P. reticulatum* shows greater potential for soil fertility improvement that can enhance crop production; and fertilizer treatment had a greater overall positive effect on fertility and bioassay crop production than the woody species.

Introduction

I served as a Peace Corps volunteer in Senegal for two years as part of the Peace Corps Master's International program at Michigan Technological University. I was assigned through the Ministry of Environment and Protection of Nature to serve as an agroforestry extension agent in Dialacoto, a rural village in the Tambacounda region. My primary responsibility was to promote the adoption of agroforestry technologies by Senegalese farmers to increase the resilience of the farming system and improve agricultural production.

One of the objectives of my position was to help farmers improve soil fertility through simple, low-cost, sustainable methods. However, most smallholder farmers in Dialacoto seemed strongly resistant to common methods of soil fertility management, such as increasing fallow periods or preserving organic matter in fields. Increasing fallow periods is challenging because land is limited, and preserving organic matter in fields conflicts with common farming principles.

In discussion with farmers, the one idea that seemed to be well received was integrating trees into the cropping system as a strategy for soil conservation and crop enhancement. Incorporating trees into the growing of field crops is practicable without defying conventional farming ideology. As is, certain tree species such as *Parkinsonia biglobosa* and *Cordyla pinnata* are left in fields for their valued fruits or pods, and farmers recognize that certain crops such as millet and taro root tend to grow better under canopy of trees. However, in talking with locals and browsing relevant literature (Rhoades 1996, Ong et al. 2002, Lahmar et al. 2012), there was a lack of information to indicate which specific species would be optimal for soil improvement in Dialacoto and similar agro-ecological areas, thus prompting the aim of my research.

Background

There is growing recognition that soil fertility improvement, rather than agricultural land expansion, is the key to improved agricultural production and food security in West Africa (Sanchez et al. 1997, Bationo et al. 1998, Batjes 2001, Garrity et al. 2010). Cultivated lands are not meeting their production potential due largely to the subpar nutrient status of soils (Vanlauwe et al. 2011). Coarse texture, low activity clays, and harsh climatic conditions drive nutrient leaching, topsoil erosion, and the low nutrient status of soils in West Africa (Manlay et al. 2000). While soils of the region are inherently low in nutrients to begin with (Bationo et al. 1998), soil fertility has been further diminished by intensive cropping without sufficient nutrient additions (Bationo et al. 1995).

Traditionally, under low population densities, farmers balanced the nutrient demand of crops by letting land lay fallow for several years to replenish lost soil nutrients under natural regrowth (Bationo et al. 1998). However, under current demographic pressure, the amount of land per farmer is so low that farmers can no longer afford to let potential cultivation land lie fallow (Wezel 2000, de Graaff et al. 2011). Consequently, farmers intensively cultivate the same land year after year without substantial nutrient inputs. With each crop, soils are successively "mined" of their nutrients to the point that concentrations are insufficient for crop growth (Bationo et al. 1998, Manlay et al. 2000, de Graaff et al. 2011).

Without ample land to support sufficient fallow periods, farmers need to either modify farming practices or intensify organic and inorganic nutrient inputs to improve soil fertility. However, as is, inorganic fertilizer use is constrained by high costs and low returns due to poor agronomic efficiency (Matlon 1990, Thuo et al. 2011, Vanlauwe et al. 2011). Crop responses to inorganic fertilizers are suboptimal without sufficient organic matter inputs (Matlon 1990, Dossa 2006). Thus, many argue that soil fertility improvement must focus on management practices that increase and maintain organic matter in soil (Bationo et al. 1998, Bationo and Buerkert 2001, Vanlauwe et al. 2011, Lahmar et al. 2012). While this could be accomplished by mulching, it would require a reliance on an already scarce supply of organic resources. Most organic matter, such as crop residues and natural vegetation, is already heavily utilized as either food, fodder, fuel, or building materials (Giller et al. 2009, Lahmar et al. 2012). Adoption of a soil management technique like mulching is unlikely when it involves trade-offs with other high-value uses (Giller et al. 2009).

Incorporating trees in field cropping

Soil nutrient management could also involve fostering or leaving trees in crop fields. Integrating trees into the cropping system has the potential to improve soil fertility and nutrient use efficiency (Sanchez et al. 1997, Buresh and Tian 1998). While the impact of trees on agricultural field soil fertility is generally positive (Sanchez et al. 1997), the impact on crop yields is the result of a tradeoff between soil improvement and resource competition between crops and trees.

Trees can amend soil fertility by increasing nutrient inputs, reducing nutrient losses, and enhancing internal nutrient cycling (Sanchez et al. 1997, Buresh and Tian 1998). Relative to annual crops, trees have longer residence time, greater biomass accumulation, and more extensive root systems (Sanchez et al. 1997). With deeper and more extensive roots, trees are able to capture and cycle nutrients and water from depths beyond the reach of shallow-rooted crops (Rhoades 1996, Sanchez et al. 1997, Sirois et al. 1998). Capture and transfer of subsoil nutrients is commonly reported for more mobile nutrients like nitrate and less commonly reported for less mobile nutrients like phosphorous (Buresh and Tian 1998). Certain tree species can also increase nitrogen inputs through nitrogen-fixation (Rhoades 1996).

Additionally, trees can increase organic inputs to soil through litterfall, root decay, and by attracting animals that contribute manure (Sanchez et al. 1997). In low-input agrosystems, soil organic matter helps to retain and store nutrients, increase cation exchange capacity, increase buffering capacity in low activity clay soils, and increase soil water holding capacity (Bationo et al. 1998). Trees can also reduce nutrient losses caused by runoff and erosion (Buresh and Tian 1998). Additional benefits of trees include increased porosity through root decomposition, improved microclimate, and increased soil biological activity (Rhoades 1996, Buresh and Tian 1998, Sinare and Gordon 2015). By reducing evapotranspiration and increasing infiltration, trees can also improve the availability of soil water (Rhoades 1996).

For all of the benefits conferred by trees, there are tradeoffs. Trees can negatively influence net crop productivity through resource competition and by attracting birds and pests that damage crops (Rhoades 1996, Boffa et al. 2000). While reduced solar intensity can have a positive effect on crop production by reducing soil evaporation and increasing soil moisture, it can also limit crop production (Boffa et al. 2000). While light competition is generally the dominant limiting factor of crop growth beneath canopy, competition for water and nutrients can also have a net negative effect on crop yields (Rao et al. 1997)

Farmer-managed natural regeneration

The protection of large trees in agricultural fields has long been a standard practice in West Africa (Sirois et al. 1998, Bayala et al. 2014, Sinare and Gordon 2015). Farmers retain trees of select species favored for their multiple uses (Rhoades 1996, Bayala et al. 2014). Commonly preserved tree species include African Locust Bean *(Parkia biglobosa),* Bush Mango *(Cordyla pinnata),* African Mahogany *(Khaya senegalensis),* Tamarind *(Tamarindus indica),* Baobab *(Adansonia digitata),* and Winter Thorn *(Faidherbia albida)* (Boffa et al. 2000, Lykke 2000). However, if the aim is to improve agricultural production, the challenge with continuing this practice in its current form is two-fold; with the exception of *F. albida*, most of these species are suboptimal for crop production improvement because of their dense spreading canopies (Rhoades 1996), and most of these species are difficult to propagate in fields. Tree species like *Parkia biglobosa*, *Cordyla pinnata*, and *Khaya senegalensis*, are found almost exclusively as large old trees (Lykke 2000, Ræbild et al. 2012). Their regeneration rates are low and seedlings that regenerate are often lost to browsing (Ræbild et al. 2012). The same morphological features that make a species desirable for conservation by farmers, including large trunks, a lack of thorns, and edible fruits, also make a species less resilient to the impacts of frequent fire, deforestation, herbivory, and low rainfall (Lykke 2000). Under current conditions, further incorporating these tree species into the cropping system would require labor and resources for raising and protecting seedlings.

As a recently-popularized alternative, farmer-managed natural regeneration (FMNR) selectively manages for trees that naturally regenerate in fields. Currently, most farmers view regenerated woody plants as weeds (Ræbild et al. 2012). Before cultivation each year, they cut, clear, and burn all regenerated aboveground biomass (Bakhoum et al. 2012). Farmers believe that their fields need to be cleaned of organic matter (Wezel 2000, Tougiani et al. 2009). Since farmers coppice rather than uproot most woody plants, when plants regenerate, they typically form multiple stems, providing the appearance of undesirable sprawling shrubs rather than young, potentially-desirable trees. Under FMNR, farmers leave some of the regenerated woody plants in their field and prune them to one or two main stems so that they can more quickly mature into trees with better growth form.

FMNR requires minimal input of labor and resources. The usual barriers to farmer adoption, like money for external inputs or labor during the busy farming season (Matlon 1990, Giller et al. 2009), are not an issue with FMNR. Unlike other agroforestry technologies, it does not require raising and planting seedlings or introducing exotic species that may be limited by low survivorship (Tougiani et al. 2009, Haglund et al. 2011). It also builds upon current practices instead of introducing entirely new techniques and ideas.

FMNR was first conceptualized in the 1980s as a response to desertification and land degradation in southern Niger (Tougiani et al. 2009). The practice is now widely spread throughout Niger and has been introduced to parts of Senegal, Mali, Burkina Faso, Chad, and Ethiopia (Tougiani et al. 2009). Commonly used species include *Piliostigma reticulatum*, *Guiera senegalensis*, *Combretum spp.*, *Faidherbia albida*, and *Ziziphus spp.* (Tougiani et al. 2009) (Table 1).

Table 1. Woody species commonly used in farmer-managed natural regeneration (FMNR) (Tougiani et al. 2009).

Common name	Scientific name	Family
Camel's Foot	*Piliostigma reticulatum*	*Fabaceae*
Sabara	*Guiera senegalensis*	*Combretaceae*
Bushwillow	*Combretum spp.*	*Combretaceae*
Winter Thorn	*Faidherbia albida*	*Fabaceae*
Jujube	*Ziziphus spp.*	*Rhamnaceae*

Most research on FMNR pertains to semi-arid cropping regions where FMNR has been most widely applied, and most species-specific research focuses on *F. albida* which is one of the best known soil-improving tree species (Rhoades 1996, Garrity et al. 2010). *F. albida* is a nitrogen-fixing thorny species that is particularly compatible with cropping systems because it exhibits reverse leaf phenology, retaining its leaves throughout the dry season and shedding them during the wet growing season (Rhoades 1996). By this mechanism, *F. albida* can improve soil fertility and soil moisture without competing with crops for light. Referred to as the "albida effect", crop yields across Africa are reportedly 30-200% greater beneath *F. albida* crowns than in open areas (Rhoades 1996).

While *F. albida* is native to and widespread throughout much of Africa, it is not present in southeast Senegal. Beyond *F. albida*, optimal species for FMNR are not clearly defined. If the aim is soil fertility improvement, species should be selected for FMNR based on their influence on soil nutrient status. Plant species differ significantly in their ability to modify soil chemistry (Rhoades 1996, Sirois et al. 1998, Dossa 2006). Differences relate both to the chemical

quality of litter inputs and canopy characteristics as they relate to capture of nutrients from precipitation and dust (Rhoades 1996).

If the ultimate aim is to improve agriculture productivity, a species' influence on soil fertility should also be weighed against its influence on crop resource availability. When tree-crop competition for resources is high, trees can improve local soil function while also having a net negative impact on crop production (Sanchez et al. 1997). Decline in crop production is mostly explained by light competition as determined by a tree's growth form, with light competition greater under low spreading crowns than upright canopies (Rhoades 1996). Selection should also consider a species' ease of management (i.e. a species' capacity to quickly regenerate in fields and resist disturbance) in order to minimize farmer resource constraints and optimize farmer adoption.

On the basis of growth form and ease of management, *Combretum glutinosum* and *Piliostigma reticulatum* should be considered for FMNR in southeast Senegal and similar agro-ecological zones. Natural woody regeneration in the region is strongly dominated by the family of *Combretacea*, including *C. glutinosum*, followed by the family of *Caesalpiniacea*, comprised mainly of *P. reticulatum* (Bakhoum et al. 2012). Compared to other local woody species, *C. glutinosum* and *P. reticulatum* have relatively upright growth forms, regenerate quickly on agricultural landscapes, and are resistant to frequent disturbances such as bush fires, wood harvest, field clearing, and browsing (Bremen and Kessler 1995, Arbonnier 2004, Bakhoum et al. 2012, Ræbild et al. 2012).

Research objectives

The goal of this study was to evaluate the suitability of potential candidates for FMNR in southeast Senegal based on their influence on soil fertility. *Combretum glutinosum* and *Piliostigma reticulatum* were selected for the study based on their ease of establishment and persistence under a system of agricultural disturbance.

Piliostigma reticulatum

Piliostigma reticulatum (DC.) Hochst. is a semi-evergreen nonnodulating woody legume common to Sudano-Sahelian and Sudanian West Africa. *P. reticulatum* is commonly found in abundance on fallow land with reports of its cover exceeding 75% under favorable water availability and moderate exploitation (Bremen and Kessler 1995). It grows considerably well during the dry season (Lahmar et al. 2012). Its fruits and leaves are palatable to livestock but not a preferred forage given their high tannin content (Ayantunde et al. 2009, Lahmar et al. 2012). Livestock only browse *P. reticulatum* when

preferred forage has been exhausted. By the end of the dry season, *P. reticulatum* leaves are typically the only source of green plant material available (Lahmar et al. 2012). While not a valuable source of fodder, *P. reticulatum* is valued for its use as medicine, roofing material, timber, dyes, and firewood (Ayantunde et al. 2009, Lahmar et al. 2012).

Previous research in semi-arid West Africa indicates that intercropping with *P. reticulatum* can improve soil quality (Dossa 2006, Diedhiou et al. 2009, Dossa et al. 2012, Hernandez et al. 2015). Kizito et al. (2011) found that *P. reticulatum* can modify soil moisture through hydraulic redistribution, the passive movement of water by roots from deeper moist soil to shallower dry soil. Studies by Dossa et al. (2012) found higher concentrations of C, N, and to a lesser extent, P, beneath shrub canopy of *P. reticulatum* relative to open field sites. Additionally, Diedhiou et al. (2009) concluded that the presence of *P. reticulatum* in fields can enhance microbial diversity, shift microbial communities to fungal dominance, and ultimately increase litter decomposition.

Combretum glutinosum

Combretum glutinosum is a semi-evergreen woody species with a rounded, open crown. It is widely-distributed throughout Sahelian, Sudanese, and Guinean savannahs and woodlands (Arbonnier 2004). *C. glutinosum* sprouts profoundly following disturbance (Devineau 1999, Pare et al. 2009). Its flowering and seed dispersal take place during the dry season. Leaf shed normally occurs before the end of the rainy season quickly followed by leaf flush (Devineau 1999). Common uses for *C. glutinosum* include traditional medicine, dyes, firewood, and household construction (Arbonnier 2004, Ayantunde et al. 2009).

Republic of Senegal

The Republic of Senegal is located in West Africa and shares borders with Mauritania, Mali, Guinea, Guinea-Bissau, and the Gambia. To the west, Senegal is bound by the North Atlantic Ocean. Roughly the equivalent in size to South Dakota, the country is home to a population of 13.6 million and growing (CIA 2013). Since gaining independence from France in 1960, the nation has maintained a degree of socio-political stability that is rare in both sub-Saharan Africa and the broader muslim world to which it belongs (Villalon 1999).

More than 40% of Senegal's population of 13.6 million is concentrated in urban areas, and urbanization is growing at one of the highest annual rates in Africa at 3.3% (CIA 2013). Rapid urbanization has been catalyzed by changing climate in the predominantly agrarian country (Guèye et al. 2007). With a

population largely subsistent on agriculture, chronic drought (particularly from 1970-80 and most pronounced in Northern Senegal) has driven outmigration from rural areas (Guèye et al. 2007).

Even though less than 20% of Senegal is considered arable, the nation's economy and labor force is principally based on agriculture (Guèye et al. 2007, CIA 2013). In Senegal, as in much of West Africa, agriculture is predominantly rain-fed and small-scale. Average farm size is generally below 10 hectares (Kelley et al. 1996, Maertens and Swinnen 2009, Thuo et al. 2011). Staple crops include peanuts, millet, corn, sorghum, maize, rice, and cotton (CIA 2013).

There is also extensive management of livestock, mainly cattle and sheep, on rangeland in the north and on agricultural lands in the south. One of the dominant ethnic groups, the Fulani, are traditional pastoralists. Livestock are managed for meat and dairy production and traction for farming. Animal traction is used to transport people and supplies, perform initial cultivation, and seed and weed fields (Kelley et al. 1996). Farmers also keep livestock as a form of savings to insulate them from economic risk (Giller et al. 2009). For most rural farmers in Senegal, livestock are their household's only assets. While livestock roam freely during the dry season, many farming communities restrict livestock movement during the growing season to reduce browsing pressure on crops.

Although small in size, the Republic of Senegal is stratified into three different ecological zones, from the Sahelian zone in the North to the Sudanian-Guinean zone in the South and the Sudanian zone in between. At the most northern reaches, the Sahelian zone is characterized by rainfall of less than 300mm annually, sandy soils, and open shrub steppe (Tappan et al. 2004). At the southern end of the spectrum, rainfall exceeds 1000mm/year, soils are predominantly ferralitic with increasing clay content, and wooded savannas give way to woodlands and gallery forests (Tappan et al. 2004). Throughout all three zones, woody cover is in decline (Lykke 2000, Tappan et al. 2004). The responsible mechanisms vary by region but include: changes in rainfall intensity and frequency, browsing pressure, farming practices that expose soils to water and wind erosion, and charcoal production (Tappan et al. 2004).

Methods

Study site

The study site was located in Dialacoto (13.316285° N, 13.284699° W), a village of approximately 3,500 people in the Tambacounda region of southeast Senegal. Located on the national road N7 to Guinea, Dialacoto lies on the edge of the 913,000ha Niokolo-Koba National Park and Biosphere Reserve and the 127,000ha Diambour Classified Forest (forestland that is federally protected and managed).

Situated at the southern edge of the Sudanian zone, Dialacoto's tropical Sudanese climate is distinguished by a long dry season and a relatively short rainy season (Kessler and Breman 1991). The single growing period occurs during the rainy season from June to October, with annual rainfall between 800 – 1000mm. Mean daily minimum and maximum temperatures are 27 – 41°C during the hottest months (April – May) and 20 – 35°C during the coldest months (Dec – Jan). The dry season is characterized by harsh Harmattan winds (dry dusty winds that blow in from the Sahara Desert) and frequent anthropogenic bush fires.

Soils are classified as shallow loamy and gravelly over laterite on plateaus, and deep, sandy to loamy, leached tropical ferruginous in valleys and on terraces where the majority of agriculture takes place (Tappan et al. 2004). The dominant land cover type is woodland savanna (Tappan et al. 2004). Dominant woody species include: *Combretacea spp., Manguifera indica, Terminalia macroptera, Cordyla pinnata, Pterocarpus erinaceus,* and *Detarium microcarpum.*

The majority of people in Dialacoto are subsistence farmers with small landholdings. Commonly cultivated crops include millet, maize, rice, sorghum, cowpea, peanut, and cotton. Given the village's proximity to protected park and forest land and the prevalence of laterite ridges around the village, arable land is limited.

Approach

Because farmer management of *C. glutinosum* and *P. reticulatum* in fields has yet to be implemented in the study area, the influence of the two species on crop production could not be measured directly. As a result, the species were evaluated based on their influence on soil fertility, which is a primary determinant of agricultural productivity. To evaluate the influence of *C. glutinosum* and *P. reticulatum* on soil fertility, soil samples were collected from beneath tree crowns and compared with control soils from agricultural fields

in both a growth experiment and chemical analyses. Because farmers in the region commonly apply low levels of chemical fertilizer to crop fields, soils were also compared to field soil with fertilizer treatment.

Soil sampling

Soil samples were collected from sites with trees and from adjacent agricultural fields without trees. Sampling sites with trees were selected based on the presence of mature individuals of *Piliostigma reticulatum* and *Combretum glutinosum* near to fields (< approximately 30m from field edge) owned by trusted farmers who had not applied chemical fertilizer to the soil within the past three years. Sampling sites were all kept within a region of one-km radius to minimize inter-site variability in soil characteristics due to geography and surficial geology.

For each woody species, five individuals were selected for soil sampling. To minimize between-species variability due to size class, mature individuals were selected that were similar in size. Tree size was assessed based on measurements of height and diameter at breast height (DBH). Tree height was measured using a clinometer (SUUNTO, Vantaa, Finland), and DBH was measured using a diameter tape (Forestry Suppliers, Inc., Jackson, MS). Additionally, individuals were selected based on their relative isolation in order to minimize the influence of other trees on soil nutrient status. Isolation was determined based on visual inspection of both the tree canopy and the composition of leaf litter beneath the crown. Individuals were selected if leaf litter beneath their crown predominantly originated from the species of interest. For each individual tree, soil subsamples were collected at four randomly selected points beneath the crown. In total, twenty subsamples were collected for each tree species (5 individuals x 4 subsamples/individual) and bulked together. For each sampling point, square plots of twenty by twenty-cm were delineated for soil collection.

Table 2. Characteristics of trees used in the study. Values are means ± 1 standard deviation (n = 5).

Tree species	Family	Height (m)	DBH (cm)
Piliostigma reticulatum	Fabaceae	9.6 ± 1.7	35.9 ± 8.5
Combretum glutinosum	Combretaceae	12.9 ± 3.2	23.8 ± 2.3

For comparison, soil was also collected from adjacent fields without trees and without a recent history of inorganic fertilizer application. Lack of recent fertilizer application was verified by communication with the respective farmer and by selecting field sites that had been previously cropped with legumes. Local farmers do not usually apply inorganic fertilizer when cultivating leguminous crops like cowpeas and peanuts. Sites previously cropped with legumes were also selected because it is common local practice to grow millet or maize following a leguminous crop.

Samples were collected from four different fields with subsamples collected at five random points. In total, twenty samples representing field soil without trees were collected (5 samples per field x 4 fields) and bulked together. For each sampling point, square plots of forty by forty-cm were delineated, instead of the twenty by twenty-cm used for tree plots, in order to provide twice as much field soil for experimentation while maintaining consistency in the number of sampling points for each soil type.

For all sampling points, soil was collected from the uppermost twenty-cm of each plot using a stainless steel trowel. Leaf litter was removed from the soil surface prior to sampling. Following collection, soil samples were air dried, crushed, passed through a two-mm sieve, and thoroughly mixed.

Plant growth experiment
To assess the fertility of soils beneath *C. glutinosum* and *P. reticulatum*, a common garden bioassay experiment was performed using crop growth and biomass production as indicators of soil fertility. Two common cereal crops, millet *(Pennisetum glaucum)* and maize *(Zea mays)*, were grown in pots filled with one of four different soil treatments:
- **Field** – soil sampled from fields
- **Field +** – soil sampled from fields and experimentally amended with chemical fertilizer
- ***P. reticulatum*** – soil sampled from beneath the crowns of *Piliostigma reticulatum* trees
- ***C. glutinosum*** – soil sampled from beneath the crowns of *Combretum glutinosum* trees

Crop production and growth measurement
Planting specifications and timing matched local farming practices. In July 2016, at the start of the local planting season, millet and maize seeds were sown in two-gallon polyethylene plastic pots filled with seven-kilograms of soil. To minimize light competition between plants, pots were spaced 50-cm apart within rows and 70-cm apart between rows. A local variety of maize, var. *synthetic c*, was sown at a density of six per pot at two-cm depth, and a local

landrace of millet, var. *nyo messengo*, was sown at a density of twelve per pot at two-cm depth.

Pots were arranged in a randomized complete block design (RCBD). Each treatment was replicated five times. Blocks were oriented along the east-west axis to account for differences in shading imposed by a nearby building. The total number of experimental pots was 40 (2 types of crops x 4 soil treatments x 5 replications). Additional non-experimental pots were placed on north and south edges (perpendicular to blocks) to minimize edge effects.

Block A	2	4	7	6	5	8	1	3
Block B	8	2	4	5	7	6	1	3
Block C	2	3	7	5	4	1	8	6
Block D	5	3	8	7	1	4	6	2
Block E	7	8	6	4	2	5	3	1

Figure 1. Randomized complete block design. (1) millet grown in field soil, (2) millet grown in field soil amended with fertilizer, (3) millet grown in soil from beneath *C. glutinosum*, (4) millet grown in soil from beneath *P. reticulatum*, (5) maize grown in field soil, (6) maize grown in field soil amended with fertilizer, (7) maize grown in soil from beneath *C. glutinosum*, (8) maize grown in soil from beneath *P. reticulatum*.

Ten days after sowing (DAS), maize and millet seedlings were thinned to one per pot, leaving the individual that appeared the most robust. Weeding was performed manually as needed. Pots in the fertilized treatment were chemically fertilized per local common practice. Fertilizer treatment was applied as solid NPK (15-15-15) and solid urea. Chemical fertilizers were applied evenly along the edge of the pot at two-cm depth beneath the soil surface. NPK was applied 20 DAS and urea was applied 40 DAS. Both fertilizers were applied at a dose of 0.1 grams per pot, the approximate equivalent of 50kg per hectare.

When rainfall was inadequate to maintain soil moisture, pots were watered twice a day. All pots received uniform water treatment. Seedlings were monitored for presence of pests and treated as needed. When pests were observed on most plants 25 DAS, all pots were treated with chemical pesticide (dimethoate) applied by hand pump sprayer.

Nondestructive measurements of growth were performed every 10 days beginning 10 DAS. Plant height and maize ear height were measured with a measuring tape and root collar diameter was measured using a Vernier caliper

(Vernier type 6914, Scienceware, Pequannock, NJ). Observations were recorded including presence of pests, disease, and leaf discoloration.

Crop biomass measurement

At 105 DAS, maize and millet plants had reached maturity, and they were harvested and measured for biomass. Plants were separated into root, shoot, and fruit parts. Shoots were separated at one-cm above the soil surface. Roots were separated from the soil by rinsing and sieving. Plant parts were freshly weighed at harvest and then solar dried for two weeks. Drying plant parts were weighed daily during the hottest hour of the day until weights remained constant. Dry weights were recorded at constant weight.

Soil physical and chemical analysis

Soil samples for laboratory analysis were collected from the experimental soil before potting and after harvest. Air-dried soils were stored in Whirl-pak plastic bags pending analysis. Samples were analyzed at Michigan Technological University in Houghton, MI. Soil pH was determined with a glass electrode in a 1:1 soil: deionized water suspension. Percent silt, clay, and sand were determined for composites of each soil type by the Bouyoucos hydrometer method (Gee and Bauder 1986). Total C and N were determined by combustion analysis with a Costech elemental analyzer (ECS 4010; Costech Analytical Technologies, Inc. Valencia, CA). Exchangeable cations, K^+, Ca^{2+}, and Mg^{2+}, were extracted with 1M NH_4Cl and concentrations were determined by Perkin-Elmer ICP-OES (Optima 7000 DV; Perkin-Elmer, Waltham, MA). Bioavailable soil P was determined using the Mehlich I extraction method with a ratio of five grams soil to twenty milliliters of a 0.05 M HCl and 0.0125 M H_2SO_4 solution (Kuo 1996). Extracted P concentration was determined colorimetrically by reacting with ammonium molybdate and measuring absorbance at 882 nm in a Spectronic 20 Genesys spectrophotometer (Thermo Fisher Scientific, Waltham, MA) (Kuo 1996).

Soil incubation

A twenty-eight day aerobic lab incubation was conducted to evaluate nitrogen mineralization (Curtin and Campbell 2008). Prior to incubation, air-dried soils had been stored in sealed plastic bags for seven months post-sampling. Five grams of soil were weighed into two-ounce clear plastic cups. Deionized water was added to each sample to achieve approximate field capacity. Soils were covered with a plastic lid with a single aeration hole. Soils were incubated in the dark at approximately 22°C. Each week, soils were weighed in their containers, and water was amended to return soils to their initial incubation soil moisture content.

Soils were analyzed for NO_3^-–N and NH_4^+–N contents at time zero and at twenty-eight days. Nitrate and ammonium was extracted from each five-gram soil sample with twenty-five milliliters of 2M KCl. Extracts were frozen pending analysis. Nitrate and ammonium were analyzed using a Rapid Flow Analyzer (Perstorp 3550 EnviroFlow; Perstorp Analytical Inc., Silver Spring, MD). Percent moisture was determined by oven-drying subsamples at 105°C for twenty-four hours and weighing before and after drying. Net nitrogen mineralization was calculated as the change in combined NO_3^-–N and NH_4^+–N per kilogram of dry soil from time zero to twenty-eight days.

Statistical analysis

All statistical analyses were performed with SPSS statistics software (version 24.0, SPSS Inc.). For both experimental and soils data, analysis of variance (ANOVA) was conducted. Normality of residuals was demonstrated by the Shapiro-Wilk and Kolmogorov-Smirnov tests, and homogeneity of variances was demonstrated by Levene's test. If ANOVA indicated statistical significance, multiple comparisons were computed post-hoc using Tukey's honestly significant difference (HSD) test. Although the experiment was designed with blocking to account for differential shading, preliminary analyses showed no significant block effect, likely due to the predominance of overcast weather during the 2016 growing season. ANOVA models for block designs assume additive block effects (citation). However, Tukey's test for non-additivity did not demonstrate additivity of blocks for this study. As a result, data was analyzed without blocking. Linear regression using least squares was conducted to evaluate the relationship between total organic carbon and soil nutrient concentrations. For all analyses, level of $p < 0.05$ was used as the minimum for significance.

Results and Discussion

Texture and pH of soils

All soils were loamy sand in texture. Clay content ranged from 9-11%. Sand content ranged from 65-69% and was greatest beneath trees. While all soils were classified as slightly acidic, pH was significantly less acidic (p < 0.001) under trees (pH 6.5) than in open fields (pH 5.6) (Table 3). Diedhiou et al. (2009) reported similar values beneath (pH 6.4) and outside (pH 5.8) *P. reticulatum* shrub canopy.

The lower pH in agricultural fields likely results from the lower organic matter content. Continuous cultivation without restitution of organic matter can lead to low soil organic matter content and subsequent soil acidification (Bationo et al. 1995). Additionally, repeated chemical fertilizer inputs in the absence of organic matter inputs have been shown to reduce soil production potential through acidification (Matlon 1990). While field site soils had not been amended with fertilizer within the past three years, it is likely that fertilizer was applied to the soil at one time or another under different cropping systems (e.g. maize, sorghum, or cotton cropping).

Chemical composition of soils

Independent of tree species, soil chemical analyses indicated significant differences (p < 0.01) in soil fertility beneath tree canopy and in open fields (Table 3). Indices of soil fertility (total organic C, total N, exchangeable K, Mg, and Ca, and available P) were greater beneath *P. reticulatum* and *C. glutinosum* compared to adjacent open fields. On average, total organic C was 35% greater, total N was 31% greater, exchangeable K, Mg, and Ca were 81%, 42%, and 37% greater respectively, and (Mehlich I) available P was 67% greater. The only analyzed parameter that did not differ significantly between soils was C:N ratio (Table 3).

For all but exchangeable K, there was no significant difference in soil nutrient concentrations between the two tree species (Table 3). For exchangeable K, concentrations were greater in soil beneath *P. reticulatum* trees than *C. glutinosum* trees (p < 0.001). Additionally, the effect of soil type on nutrients was greatest for exchangeable K with the average concentration two-fold higher under *P. reticulatum* than in fields.

Table 3. Chemical composition of soil samples (0-20cm depth) prior to growth experiment. Soil ID: (C) soil from beneath *C. glutinosum* trees, (F) field soil, (P) soil from beneath *P. reticulatum* trees. Values are means ± 1 standard error (n = 5). Treatment d.f. = (2, 12).

			% Total Concentration			Exchangeable Cations (cmol$_c$ kg^{-1})			Available (mg kg^{-1})
		pH	C	N	C/N	K	Ca	Mg	P
Soil ID	C	6.5 [a] ± 0.2	0.76 [a] ± 0.03	0.06 [a] ± 0.002	13.5 ± 0.3	0.12 [b] ± 0.004	1.16 [a] ± 0.03	0.43 [a] ± 0.01	7.1 [a] ± 2.0
	F	5.6 [b] ± 0.2	0.56 [b] ± 0.01	0.04 [b] ± 0.000	14.1 ± 0.3	0.07 [c] ± 0.005	0.82 [b] ± 0.04	0.319 [b] ± 0.02	3.9 [b] ± 0.2
	P	6.5 [a] ± 0.2	0.75 [a] ± 0.02	0.05 [a] ± 0.002	14.0 ± 0.4	0.15 [a] ± 0.007	1.17 [a] ± 0.05	0.443 [a] ± 0.02	5.9 [a] ± 2.1
ANOVA	F	32.8	27.2	19	0.84	49.0	26.2	23.4	23.1
	p	<0.001	<0.001	0.002	0.46	<0.001	<0.001	<0.001	<0.001

Means in the same column followed by the same letter are not significantly different at the α = 0.05 level using Tukey's HSD.

The significantly higher total organic C and nutrient concentrations in soil beneath trees is consistent with results from similar studies (Sirois et al. 1998, Iyamuremye et al. 2000, Diedhiou et al. 2009, Diakhaté et al. 2013, Sinare and Gordon 2015). Similar results have attributed higher nutrient concentrations to tree litter input, (Bernhard-Reversat 1982, Manlay et al. 2000, Diedhiou et al. 2009), root turnover and exudates (Rao et al. 1997, Diedhiou et al. 2009), and Harmattan dust that is captured by vegetation and deposited under canopies during the rainy season via stemflow and throughfall (Stoorvogel et al. 1997, Harris 1999, Breuning-Madsen et al. 2012). In low fertility soils, dust carried in by Harmattan winds can be a significant source of cations and P that is readily available for plant uptake (Rhoades 1996, Stoorvogel et al. 1997, Harris 1999, Breuning-Madsen et al. 2012). Scott-Wendt et al. (1998) found that the chemical composition of Harmattan dust sampled in Niger was analogous to that of agriculturally productive soils; both had relatively high pH (≥ 6.5) and available cation concentrations relative to soils that were considered unproductive.

Soil organic carbon and nitrogen

Total organic C in soils ranged from 0.5% in fields to 0.7% beneath trees, and was strongly correlated with total N ($r = 0.96$, $p < 0.0001$) (Table 4), which ranged from 0.04% in fields to 0.06% beneath trees (Table 3). These results are typical of the coarse, low-activity clay soils that characterize the greater agro-ecological zone (Manu et al. 1991, Bationo et al. 1998, Bationo and Buerkert 2001). Diedhiou et al. (2009) reported a range of total C values between 0.3 – 0.6% for soils beneath and outside of *P. reticulatum* shrub canopy. Bationo et al. (2007) reported 0.2 – 0.5% organic C for bush fields and 0.5 – 1.0% for fields nearer to village centers that receive more organic inputs. The total N values reported here are also within the range reported by Bationo et al. (2007), with field total N similar to Bationo values for bush fields (0.02 – 0.05%), and total N beneath trees similar to Bationo values for village fields with higher organic inputs (0.05 – 0.09%).

Table 4. Linear correlation of soil total organic carbon and analyzed soil nutrients [total N, mineralized N (N_{min}), available P, and exchangeable K, Ca, and Mg].

	Coefficient of correlation (r)					
	Total **N**	**N_{min}**	Avail. **P**	Exch. **K**	Exch. **Ca**	Exch. **Mg**
Total Organic C	0.96**	0.85**	0.73*	0.80**	0.74**	0.77**

* Correlation significant at $p < 0.01$ ** Correlation significant at $p < 0.001$

Because of the limited nutrient exchange and storage capacity of local clays, nutrient holding capacity is often more strongly correlated to organic matter than clay content (Manu et al. 1991, Bationo et al. 1998, Wezel et al. 2000). Nitrogen in particular is nearly exclusively contained within soil organic matter in tropical African soils (Bationo et al. 1998, Dossa 2006), hence the high correlation of total N with total organic C relative to the other nutrients in the study (Table 4).

Soil organic carbon and phosphorous

Mehlich I available P ranged from 3.9 – 7.1 mg kg^{-1} (Table 3). In P-limited soils like those of Senegal, studies indicate that organic C is crucial to supplying available P through mineralization, complexation of metal cations by organic acids, and displacement of phosphate anions from sorption sites (Manu et al. 1991, Dossa 2006). This is reflected in the strong positive correlation between total organic C and available P ($r = 0.73$, $p= 0.0022$) (Table 4). However, as

evidenced by the comparative correlation strength of N (r = 0.96) and P (r = 0.73) with total organic C, association with organic matter content is not as strong for phosphorous as it is for nitrogen (Parfitt 1979, Bationo et al. 1998).

Nitrogen mineralization

Availability of nitrogen is often more related to measures of production over time than measures of different nitrogen forms at a single point in time (Rhoades 1995). Hence, nitrogen mineralization, as measured in this study, is likely a more reliable index of plant-available nitrogen than static measures of NO_3^-–N and NH_4^+–N pools. During the twenty-eight day soil incubation, net nitrogen mineralization was significantly greater in soil from beneath *P. reticulatum* than in open fields (p = 0.04, Table 5). Net mineralization in soil from beneath *P. reticulatum* crowns exceeded open fields by more than 160%. On average, nitrogen was mineralized at a rate of 1.41 N mg kg^{-1} d^{-1} beneath *P. reticulatum*, 1.25 N mg kg^{-1} d^{-1} beneath *C. glutinosum*, and 0.92 mg kg^{-1} d^{-1} in open fields. Overall, there was a strong correlation between mineralized and total nitrogen (r = 0.84, p < 0.001, Table 5).

Table 5. Initial NO_3^-–N and NH_4^+–N in soils, net mineralized N (N_{min}) obtained by twenty-eight day aerobic incubation, percent final NO_3^-–N of total inorganic N (N_{Inorg}), and percent mineralized N to total N. Soil ID: (C) soil from beneath *C. glutinosum* trees, (F) field soil, (F+) field soil amended with fertilizer, (P) soil from beneath *P. reticulatum* trees. Values are means ± 1 standard error (n = 5). Treatment d.f. = (2, 12).

| | | Initial | | Final | | |
| | | | | | | |
	Soil ID	NH_4^+–N (mg N kg^{-1})	NO_3^-–N (mg N kg^{-1})	NO_3^-–N/ N_{Inorg} (%)	N_{min} (mg N kg^{-1} d^{-1})	N_{min}/ N_{total} (%)
Soil ID	C	7.1 [a] ± 0.27	7.5 [a] ± 0.64	68.8 [ab] ± 11.2	1.25 [ab] ± 0.06	6.4 ± 0.4
	F	13.3 [b] ± 1.4	14.8 [b] ± 2.1	58.5 [a] ± 7.5	0.92 [a] ± 0.05	6.0 ± 0.6
	P	8.9 [a] ± 0.13	13.7 [b] ± 0.5	93.6 [b] ± 0.7	1.41 [b] ± 0.06	7.4 ± 0.4
ANOVA	*F*	9.9	15.6	5.6	4.2	2.5
	p-value	<0.001	0.003	0.02	0.041	0.12

Means in the same column followed by the same letter are not significantly different at the $\alpha = 0.05$ level using Tukey's HSD.

Differences in net mineralization are commonly attributed to differences in organic matter quality that regulate decomposition, with N content and C:N ratio considered the most robust indices of mineralization in the region (Rhoades 1996, Mugendi et al. 1999, Dossa 2006). Given the similar C:N ratio for all soils, the strong correlation between mineralized and total nitrogen ($r = 0.84$, $p < 0.001$) suggests that total nitrogen content, rather than C:N ratio, was a strong determinant of nitrogen mineralization in this study. Open fields may also have experienced less nitrogen mineralization due to higher organic matter content of lignin and/or polyphenols which negatively modify decomposition (Palm et al. 1997).

Additionally, the incubations indicated that NO_3^- was the dominant form of soil inorganic nitrogen, particularly beneath tree canopies (Table 5). A predominance of NO_3^- has also been reported for in-situ soil incubations in other areas of Senegal (Iyamuremye et al. 2000, Dossa 2006). Typically, the first rains produce a large pulse of nitrification (Rhoades 1995, Asante et al. 2017). However, because NO_3^- is highly mobile, a predominance of NO_3^- suggests that nitrogen is more likely to be leached beyond crop root systems, particularly at the onset of the growing season when crops are still reliant on seed reserves (Rhoades 1995, Hoffmann et al. 2001). Though, early season leaching losses are often reduced beneath tree canopy, relative to open fields, due to tree rooting in subsoil (Buresh and Tian 1998)

Chemical composition of soils after maize harvest

Following experimental growth and harvest of maize, concentrations of organic C, total N, and exchangeable K, Ca, and Mg were significantly greater in soils from beneath trees than in amended or non-amended field soil ($p < 0.01$) (Table 6). Mehlich I available P however did not differ significantly between soil under trees and field soil amended with fertilizer ($p = 0.002$). Additionally, there was a significant difference between tree species in exchangeable K and Ca ($p < 0.001$). In both cases, cation concentrations were greater in *P. reticulatum* (K:0.066 $cmol_c$ kg^{-1}, Ca: 1.17 $cmol_c$ kg^{-1}) than *C. glutinosum* soil (K:0.048 $cmol_c$ kg^{-1}, Ca: 1.08 $cmol_c$ kg^{-1}).

Table 6. Chemical composition of soil samples following growth and harvest of maize. Soil ID: (C) soil from beneath *C. glutinosum* trees, (F) field soil, (F+) field soil amended with fertilizer, (P) soil from beneath *P. reticulatum* trees. Means ± 1 standard error. Values are means ± 1 standard error (n = 5). Treatment d.f. = (3, 16).

		% Total Concentration			Exchangeable Cations (cmol$_c$ kg^{-1})			Available (mg kg^{-1})
Soil ID		C	N	C/N	K	Ca	Mg	P
Maize	C	0.71 [a] ± 0.03	0.05 [a] ± 0.0	14.2 ± 0.6	0.048 [b] ± 0.003	1.08 [b] ± 0.01	0.36 [a] ± 0.006	4.63 [a] ± 0.06
	F	0.52 [b] ± 0.01	0.04 [b] ± 0.0	12.9 ± 0.4	0.037 [c] ± 0.001	0.72 [c] ± 0.03	0.26 [b] ±0.002	3.05 [b] ± 0.21
	F+	0.55 [b] ± 0.02	0.04 [b] ± 0.0	13.7 ± 0.4	0.035 [c] ± 0.001	0.68 [c] ± 0.01	0.24 [b] ± 0.007	3.83 [ab] ± 0.56
	P	0.73 [a] ± 0.03	0.05 [a] ± 0.0	14.0 ± 0.4	0.066 [a] ± 0.003	1.17 [a] ± 0.02	0.39 [a] ± 0.011	5.01 [a] ± 0.21
ANOVA	F	23.8	41.0	1.8	39.9	166.5	105.9	7.5
	p-value	<0.001	<0.001	0.18	<0.001	<0.001	<0.001	0.002

Chemical composition of soils after millet harvest

Following experimental growth and harvest of millet, concentrations of organic C, total N, and exchangeable Ca and Mg were significantly greater in soils from beneath trees than in amended or non-amended field soil (p < 0.001) (Table 7). Exchangeable K however was only significantly greater in *P. reticulatum* soil. Available P concentrations were greatest in *P. reticulatum* soil, but unlike other nutrient concentrations, P was also significantly greater in fertilizer amended field soil than in control field soil. This positive effect of fertilizer on available P is consistent with the results for maize growth.

Table 7. Chemical composition of soil samples following growth and harvest of millet. Soil ID: (C) soil from beneath *C. glutinosum* trees, (F) field soil, (F+) field soil amended with fertilizer, (P) soil from beneath *P. reticulatum* trees. Means ± 1 standard error. Values are means ± 1 standard error (n = 5). Treatment d.f. = (3, 16).

	Soil ID	% Total Concentration			Exchangeable Cations (cmol$_c$ kg^{-1})			Available (mg kg^{-1})
		C	N	C/N	K	Ca	Mg	P
Millet	C	0.732 [a] ± 0.026	0.052 [a] ± 0.002	14.1 ± 0.3	0.034 [b] ± 0.002	1.014 [b] ± 0.044	0.335 [a] ± 0.019	3.85 [b] ± 0.07
	F	0.554 [b] ± 0.026	0.040 [b] ± 0.0	13.9 ± 0.6	0.029 [b] ± 0.001	0.695 [c] ± 0.008	0.260 [b] ± 0.012	2.16 [c] ± 0.07
	F+	0.536 [b] ± 0.021	0.040 [b] ± 0.0	13.5 ± 0.5	0.030 [b] ± 0.003	0.703 [c] ± 0.022	0.246 [b] ± 0.007	3.71 [b] ± 0.49
	P	0.744 [a] ± 0.031	0.052 [a] ± 0.002	14.3 ± 0.2	0.050 [a] ± 0.005	1.190 [a] ± 0.050	0.371 [a] ± 0.006	5.25 [a] ± 0.42
ANOVA	*F*	18.0	24.0	0.72	9.40	49.15	24.21	15.25
	p-value	<0.001	<0.001	0.56	<0.001	<0.001	<0.001	<0.001

Maize growth and biomass

Parameters of maize growth and biomass production differed significantly amongst soil treatments (p < 0.05) (Table 8). Maize grown in field soil treated with chemical fertilizer exceeded control treatments in all parameters of growth performance and biomass production. Maize grown in soil from beneath *P. reticulatum* also produced significantly greater biomass and root collar diameter (RCD) than control treatments (p < 0.001). Final mean RCD was 12.2mm (s.e. = ±1.1) in *P. reticulatum* soil and 14.9mm (s.e. = ±0.8) in fertilized soil, which was 31% and 60% greater, respectively than in control field soil (Table 8). The positive effect of *P. reticulatum* and fertilizer treatments on RCD became evident early-on, beginning between thirty-five to forty-five days after sowing (Figure 2).

Table 8. Effects of soil treatments on final maize biomass, plant height, root collar diameter, and ear height. Treatments: soil from beneath *C. glutinosum* trees, field soil, field soil amended with fertilizer, soil from beneath *P. reticulatum* trees. Values are means ± 1 standard error (n = 5). Treatment d.f. = (3, 16).

	Treatments				ANOVA	
	C. glutinosum	Field	Field +	*P. reticulatum*	F	p-value
Total biomass (g)	21.7 [a] ± 2.0	23.1 [a] ± 1.1	54.6 [b] ± 5.6	45.8 [b] ± 7.4	11.6	<0.001
Root biomass (g)	6.6 [ab] ± 0.7	4.9 [a] ± 0.3	11.8 [c] ± 0.5	9.8 [bc] ± 1.8	9.2	0.001
Shoot biomass (g)	15.1 [a] ± 1.5	18.2 [a] ± 1.4	42.5 [b] ± 5.4	36.0 [b] ± 5.7	10.9	<0.001
Shoot/root biomass	2.35 [b] ± 0.2	3.82 [a] ± 0.5	3.59 [a] ± 0.4	3.77 [a] ± 0.3	3.7	0.034
Plant height (cm)	119.7 [ab] ± 7.4	112.9 [a] ±7.2	144.9 [b] ± 6.2	129.5 [ab] ± 4.4	4.6	0.018
Root collar diameter (mm)	10.0 [a] ± 0.3	9.3 [a] ± 0.3	14.9 [b] ±0.8	12.2 [b] ± 1.0	14.5	<0.001
Lower ear height (cm)	43.7 [ab] ± 3.3	35.2 [a] ± 1.8	48.3 [b] ± 2.9	46.4 [b] ± 2.9	4.3	0.021

Means in the same row followed by the same letter are not significantly different at the α = 0.05 level using Tukey's HSD
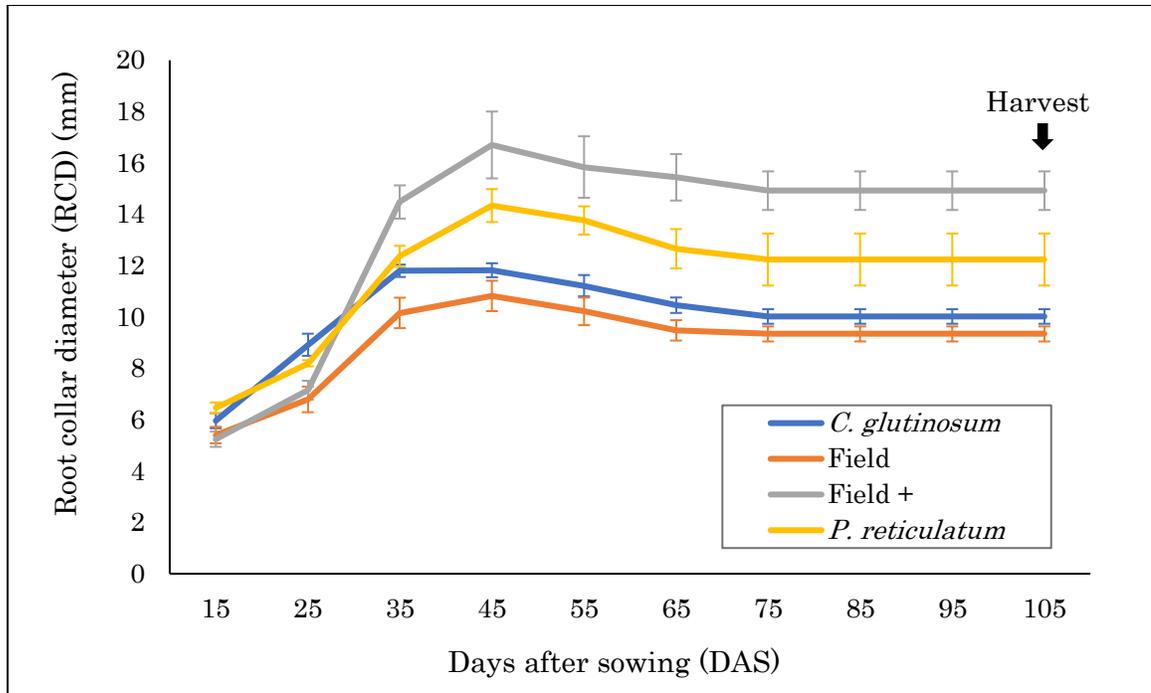
Figure 2. Effects of soil treatments on root collar diameter of maize over time. Treatments: soil from beneath *C. glutinosum* trees, field soil, field soil amended with fertilizer, soil from beneath *P. reticulatum* trees. Bars indicate standard error.
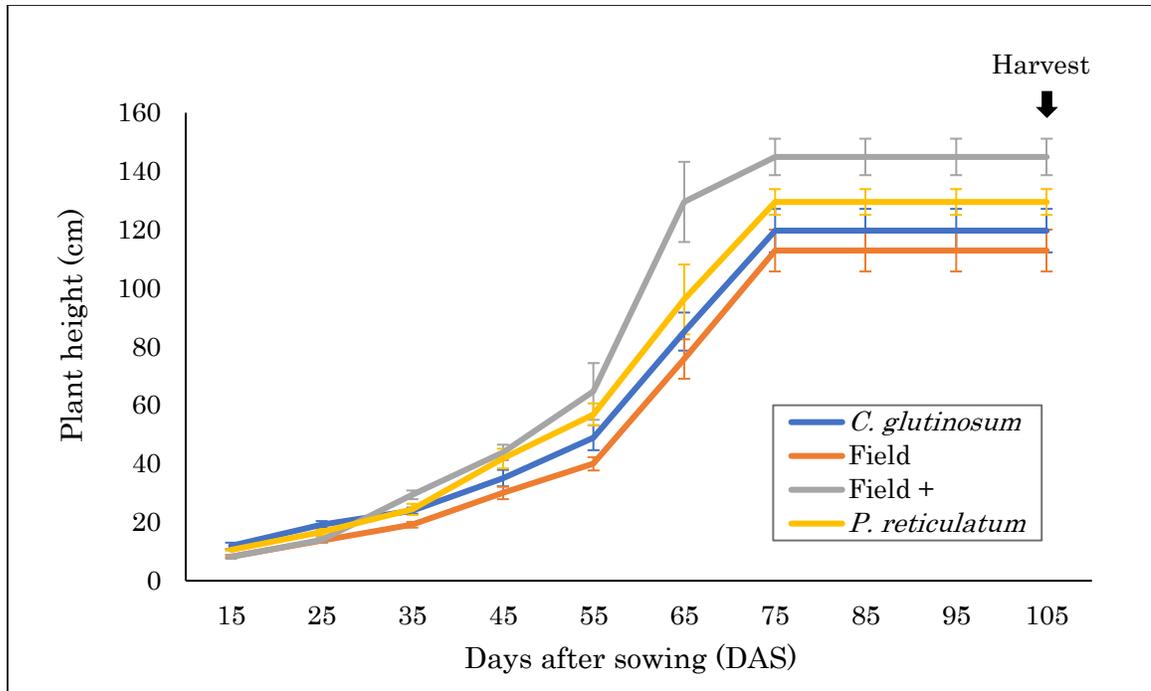
Figure 3. Effects of soil treatments on mean stem height of maize over time. Treatments: soil from beneath *C. glutinosum* trees, field soil, field soil amended with fertilizer, soil from beneath *P. reticulatum* trees. Bars indicate standard error.

Maize grown in soil from beneath *C. glutinosum* did not differ significantly from control treatments (field) for all parameters other than shoot:root biomass ratio (Table 8). Under *C. glutinosum* soil treatments, maize shoot:root biomass was significantly less ($p = 0.034$) than under *P. reticulatum* or control treatments. When nutrients or soil moisture are growth-limiting, more dry matter is allocated to roots, resulting in lower shoot:root ratios (Shank 1945). Given that texture and water treatment were similar for all soils and P availability was not lower beneath *C. glutinosum* (Table 3), the lower shoot:root ratio is unlikely an indication of moisture or P limitation. Instead, the shoot:root ratio and the absence of *C. glutinosum* effect on maize growth could be attributed to N or K availability. Unlike *P. reticulatum, C. glutinosum* did not have a positive effect on nitrogen mineralization (Table 5); and exchangeable K was significantly higher ($p < 0.001$) under *P. reticulatum* than *C. glutinosum* (Table 3).
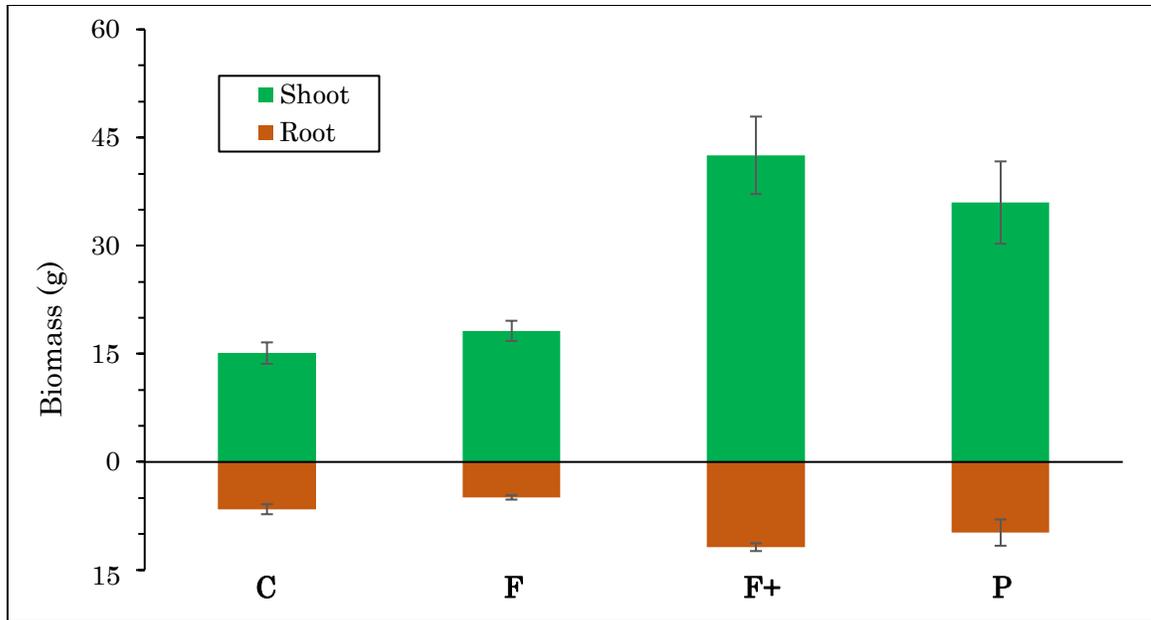
Figure 4. Effects of soil treatments on maize biomass. Treatments: (C) soil from beneath *C. glutinosum* trees, (F) field soil, (F+) field soil amended with fertilizer, (P) soil from beneath *P. reticulatum* trees. Bars indicate standard error.

Maize plants did not yield grain in any treatment. While all plants produced both male and female flowers, pollen shed was complete before silk emergence, thereby preventing fertilization and grain production. Failure to produce due to delayed silking is commonly explained by moisture stress, particularly during the tasseling-silking stage (Sah and Zamora 2005, Lobell et al. 2011). However, common visual indicators of moisture stress, including leaf curl or shedding of lower leaves (Miller and Smith 1973), were not readily apparent, signifying that delayed silking may have had a lesser known cause or combination of causes.

It is likely that pot size imposed limitations on maize performance. Under the limited growth space of pots, plant growth is often reduced as a result of reduced resource supply, increased soil temperature, and reduced water holding capacity (Yang et al. 2010, Poorter et al. 2012). Poorter et al. (2012) reported that the percent of total root mass present within four-mm of pot walls often exceeds 50%. Pot dynamics can cause root growth to concentrate in areas near pot walls where temperature fluctuations are highest and walls can impede root growth (Poorter et al. 2012). In this study, a similar trend of root accumulation near pot edges was observed for all treatments at harvest, with the implication that pots limited root growth and potential nutrient acquisition.

Lack of grain yield may also be an indicator of the overall fertility status of the soils. Although *P. reticulatum* and mineral fertilizer positively influenced maize production, a degree of influence significant enough to improve grain yield may require inputs of both organic and inorganic fertilizer (Bationo and Buerkert 2001). On their own, the organic inputs of *P. reticulatum* and the inorganic inputs of fertilizer may not have been sufficient to overcome the nutrient deficiencies of the soil.

While grain yields were not obtained, measures of plant biomass (excluding grain) are commonly used to predict grain yields. Plant biomass and grain yield have been closely correlated under a wide range of conditions for a variety of maize cultivars (Sinclair et al. 1990, Zere at al. 2005, Ceccon 2015). For root, shoot, and total biomass, maize grown in both *P. reticulatum* soil and amended field soil produced significantly greater values than control soil ($p \leq 0.001$, Table 8). Total biomass was nearly 100% greater in *P. reticulatum* soils and 136% greater in fertilized soils than in control soils (Figure 4), signifying that fertilizer treatment and intercropping with *P. reticulatum* has the potential to improve maize grain yields.

As a heavy feeder of nitrogen, maize production is often limited by nitrogen availability, particularly in low fertility soils (Bationo et al. 1998). Given the low inherent nitrogen levels of soils in the study region, the positive response of maize performance to *P. reticulatum* and fertilizer treatment is likely due to changes in soil nitrogen availability. Relative to other common crops in the study region, it is widely accepted that maize responds well to additions of nitrogen fertilizer, with the magnitude of response dependent on the nutrient and organic matter status of soils (Vanlauwe et al. 2011). The greater than two-fold increase in maize biomass with only moderate additions of fertilizer reflects the relatively low total nitrogen content (0.04%) of field soils, suggesting relatively high nitrogen agronomic efficiency of maize production.

Millet growth and biomass
There was no significant treatment effect on millet stem height, root collar diameter, and shoot and grain biomass (Table 9). The only parameter that differed significantly between treatments was root biomass, with millet grown in amended soil yielding significantly greater root biomass than millet grown in *P. reticulatum* soil.

Table 9. Effects of soil treatments on final millet biomass, and height and root collar diameter. Values are means ± 1 standard error (n = 5). Treatment d.f. = (3, 16).

	Treatments	ANOVA

	C. glutinosum	Field	Field +	P. reticulatum	F	p-value
Total biomass (g)	57.6 ± 13.5	70.9 ± 16.2	191.1 ± 79.5	59.0 ± 14.9	2.4	0.11
Root biomass (g)	12.8 [ab] ± 3.4	14.9 [ab] ± 2.6	32.9 [a] ± 10.1	7.9 [b] ± 1.5	3.9	0.03
Shoot biomass (g)	30.0 ± 6.8	43.5 ± 11.8	110.2 ± 55.4	30.4 ± 8.0	1.8	0.19
Grain biomass (g)	14.9 ± 5.1	12.4 ± 3.0	48.0 ± 19.3	20.7 ± 6.6	2.4	0.11
Shoot/root biomass	2.86 ± 0.82	2.87 ± 0.62	2.97 ± 0.72	3.74 ± 0.41	0.4	0.75
Plant height (cm)	141.1 ± 16.5	154.7 ± 12.7	192.7 ± 13.5	168.0 ± 14.1	2.4	0.11
Root collar diameter (mm)	12.5 ± 1.2	16.6 ± 2.4	17.4 ± 3.8	12.9 ± 1.8	1.0	0.41

Means in the same row followed by the same letter are not significantly different at the $\alpha = 0.05$ level using Tukey's HSD.
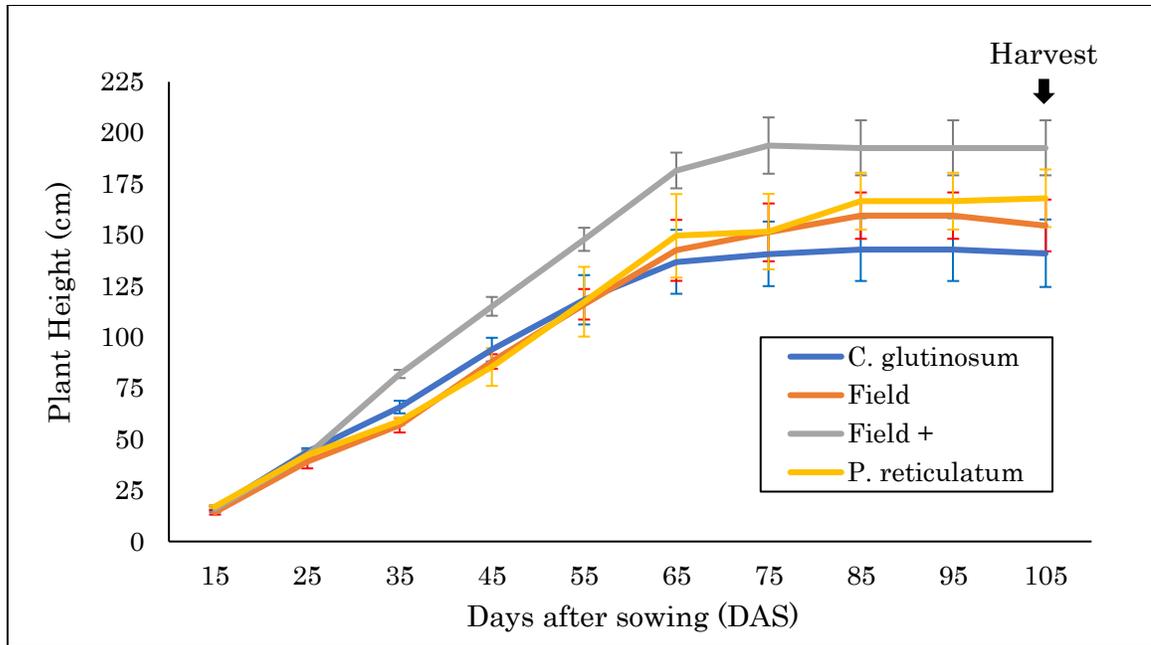
Figure 5. Effects of soil treatments on plant height of millet over time. Bars indicate standard error.
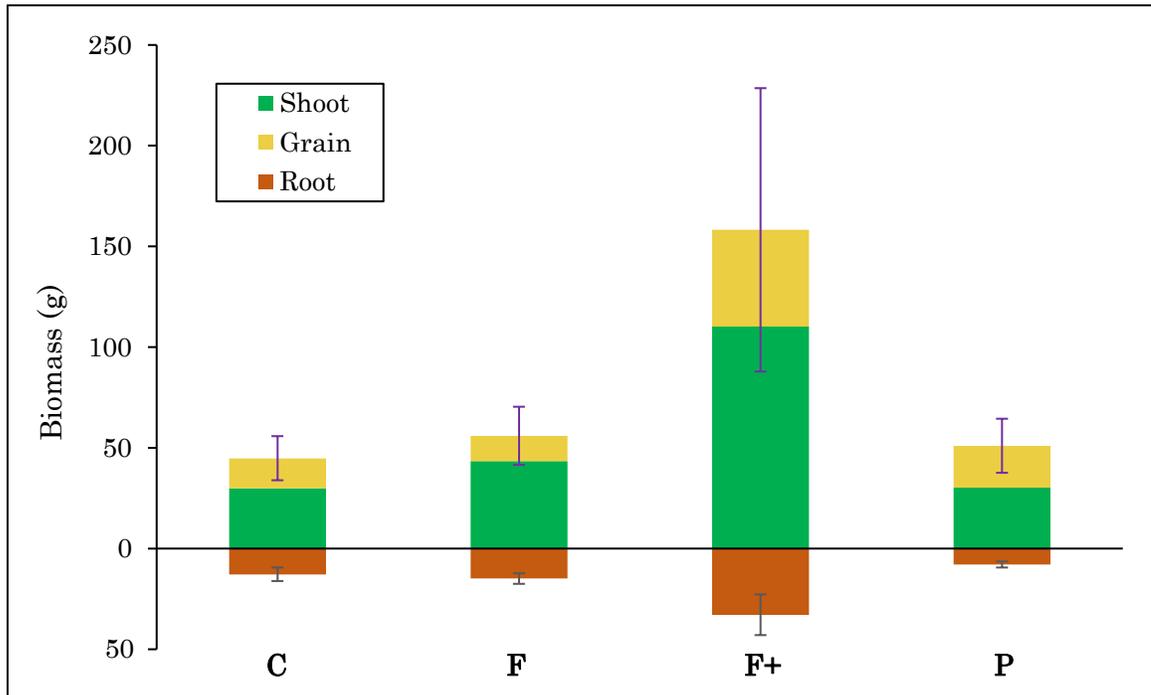

Figure 6. Effects of soil treatments on millet biomass. Treatments: (C) soil from beneath *C. glutinosum* trees, (F) field soil, (F+) field soil amended with fertilizer, (P) soil from beneath *P. reticulatum* trees. Bars indicate standard error; error bars represented in purple indicate the standard error of the combined biomass of shoot and grain.

Although the more fertile *P. reticulatum* and amended soil treatments produced greater maize biomass than the non-amended field soil, millet growth and aboveground biomass did not show significant overall differences across soil treatments. Compared to maize, millet is more tolerant to infertile soil conditions, and less responsive to certain nutrient additions (Scott-Wendt et al. 1988). Nitrogen additions generally have less impact on millet yields than on the yields of heavy feeder crops like maize, sorghum, or rice (Matlon 1990).

Fofana (2007) suggested that the availability of phosphorous, rather than nitrogen, drives West African pearl millet production on coarse acidic soils. If pearl millet production is limited by phosphorous availability, then the levels of available phosphorous in the *P. reticulatum*, *C. glutinosum*, and field soils were not substantial enough to overcome P limitation and influence yields. P limitation, even under the canopy of trees, seems probable given that the broader region is known for inherently low levels of P and a high proportion is occluded and not available for plant uptake (Manu et al. 1991, Dossa 2006). Tree leaf litter often has a higher N:P ratio than required by crops, indicating that quantities of leaf litter sufficient to supply N may not supply sufficient P (Palm et al. 1997). Therefore, while *P. reticulatum* had a positive effect on maize production, improvement in millet production likely requires more substantial mineral inputs of P. Under less P-limited conditions, intercropping of *C. glutinosum* and *P. reticulatum* may have a more pronounced effect on millet productivity.

The lack of treatment effect may also be explained by seed genetic variability. Because pearl millet is protogynous (stigmas emerge before anthers) and produces abundant pollen throughout the flowering season, it is highly cross-pollinated, resulting in considerable genetic variability (Patil 2016). Cultivated millet, which frequently crosses with its wild progenitor, is known to display high genotypic and phenotypic variability among and within landraces (Vagadiya 2013, Busso et al. 2000). In an assessment of more than two-hundred different landraces, Brunken et al. (1977) found considerable morphological variability among plants within the same crop field.

In this case, the millet seed used in the experiment was sourced from a local non-improved landrace in order to keep the study locally-relevant. However, in doing so, the seed contributed a potential source of variation. Morphological variation due to seed genetic variability seems probable in this study considering that the total biomass of control treatments ranged from 19-110 grams with a standard deviation (36.3g) equivalent to more than half of the mean (70.1g).

Conclusion

The higher total organic C and nutrient concentrations beneath *P. reticulatum* and *C. glutinosum* indicate that these woody species can positively influence soil fertility. However, the variation in response between millet and maize to differences in soil fertility suggest that a general positive effect on crop production cannot be inferred from a positive effect on soil fertility. While maize growth and performance were significantly improved in soils beneath *P. reticulatum* and soils amended with fertilizer, the magnitude of changes in soil properties were inadequate to influence millet performance in this study. Possible effects of *P. reticulatum* and *C. glutinosum* on millet production were likely superseded by the effects of P limitation and seed genetic variability.

To persuade subsistence farmers to modify long-standing practices, the benefits of the change should be compelling enough to outweigh the risk of change and resource investment. Thus, given the potential for *P. reticulatum* to increase maize yields through improved soil fertility, farmers should consider managing this species in fields, particularly if they intend to cultivate heavy nitrogen feeders like maize. However, because the millet bioassay results in this study were highly variable, further research should be conducted to evaluate millet-tree interactions before encouraging integration of *P. reticulatum* in millet fields. Optimal tree densities within fields should also be evaluated and farmer perceptions of *P. reticulatum* should be considered.

Additionally, further research is needed to evaluate the degree of in-field tree-crop competition beneath *P. reticulatum* canopy, and whether competition can be farmer-managed by practices like pruning. It is also probable that *P. reticulatum* confers benefits to crops beyond what is evaluated in this study; given its capacity for hydraulic redistribution, *P. reticulatum's* influence on soil moisture availability should be evaluated as it relates to crop production as well as understory growth that could potentially enrich soils during the dry season.

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