SOIL FERTILITY UNDER FOUR TREE SPECIES IN THE SEMI-ARID CLIMATE OF NIGER

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ABSTRACT

A field study was conducted to investigate the impact of four tree species (Acacia albida, Acacia senegalensis, Combretum aculeatum and Piliostigma reticulatum) on soil fertility in semi-arid Niger. The species are common trees in farmers’ fields used for restoration of soil fertility. Soil composite samples were collected along four transects at different distances from the tree trunk, at five levels of soil depth (0-10, 10-20, 20-30, 30-40 and 40-50 cm) and two age classes of trees (young and mature) to assess the effects of trees on the chemical properties of the soil (pH, organic carbon, ammonium-N, P, Na, K, Ca and Mg). The vertical distribution of all parameters, except for P, were significant, and decreased with depth. The results also showed that tree species influenced differently the distribution of the soil parameters analyzed. Soil associated with C. aculeatum was more acidic than for the other species. The organic carbon was higher beneath leguminous trees (A. albida and P. reticulatum) than non-leguminous trees (A. senegalensis and C. aculeatum). The concentration of ammonium-N, P and K were generally lower for C. aculeatum than other tree species. However, Na, Ca and Mg concentrations were generally lower with A. senegalensis than for the other tree species. Under A. albida, phosphorus concentration decreased with increasing distance from the tree trunk. And under P. reticulatum, phosphorus concentration and pH increased with tree age. Based on the present project, all the four tree species under study can be recommended for use in farmers’ fields, both for reforestation and for improving soil fertility in the semi-arid zone of Niger. Farmers can also be advised to maintain more mature trees in their fields for improving crop production. Nevertheless, further research is needed to understand better the effect of distance from tree trunk and impact of tree age on soil chemical properties and crop yields.
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1. INTRODUCTION

The semi-arid sub-Saharan zone is characterized by low soil fertility, especially with regards to the low nitrogen and phosphorus content of soils, low and unpredictable rainfall, recurrent drought and high soil temperature which limits crop production (Bationo and Buerkert 2001; Sivakumar 1993). To enhance soil fertility, farmers have traditionally used a fallow agricultural system, but the growing population has increased the demand for agricultural products, which has induced farmers to reduce the period of fallow or to abandon the practice altogether in some areas. Soil degradation has increased due to deforestation to extend farmers’ fields over time. When soils are exposed to wind and water, erosion increases and the yield decreases (Wezel 2000; World Resource Institute 2013).

In Niger, food production is generally based on rain-fed agriculture and soils used for crop production are sandy, degraded and low in nitrogen and phosphorus (Bationo and Buerkert 2001; Kiari et al. 2014). To increase crop production for population needs, many techniques are being implemented by researchers to improve soil fertility and household income, particularly in West Africa. Litter and household waste, organic biomass from crop residues and mulching are among the methods used to avoid soil particle transport by wind, reduce water splash on soil, increase soil moisture and improve soil fertility (Wezel 2000). Corralling livestock on cropland, crop rotation, intercropping and micro-dosing are also utilized to improve soil fertility (Bayala et al. 2011).

In Niger, many studies show that small doses of inorganic fertilizers at sowing improve crop production (ICRISAT 2009) and the use of organic manure and crop residues increases soil organic matter (Bationo et al. 1993; Buerkert et al. 1996; Fatondji et al. 2006). However, the socioeconomic conditions limit farmers’ capacity to buy and apply inorganic fertilizers in all their fields and also the costs of transporting household waste or organic fertilizer to the field limit their use (Kiari et al. 2014). The use of crop residue for construction, fuels and fodder for livestock during the dry season (Bationo and Mokwunye 1991; Wezel 2000) also limit their use for fertility management.

Another method for fertility management is the integration of natural woody vegetation. This method improves soil fertility by enabling recycling of biomass produced by woody vegetation (Saidou et al. 2012). The population in the Sudano-sahelian zone of west Africa is the poorest in the world and the integration of woody species with crop production requires no monetary input to improve soil fertility (Bationo and Buerkert 2001; Wezel 2000). Woody species are traditionally used by small farmers to limit the climatic risk and to improve soil fertility.

In Niger, most natural vegetation consists of shrubs mixed with a few trees in some fields (Hiernaux and Le Houérou 2006; Fall et al. 2010; Bayala et al. 2010; Diarra 2011). In southern Niger, the most common shrubs and trees are *Acacia albida*, *Annona senegalensis*, *Combretum aculeatum*, *Guiera senegalensis* and *Piliostigma reticulatum*. Millet is the most common crop cultivated in Niger and its integration with woody vegetation increases the yield of grain and straw (Bayala et al. 2011; Abass et al. 2013). The soil beneath shrubs and trees forms fertile islands which are more productive than open ground (Wezel et al. 2000). Therefore, farmers put more millet seedlings in these fertile islands because the yields are higher than in the area between woody canopies (Wezel et al. 2000).
Many authors have shown the benefit of trees and shrubs on soil fertility (Maiga 1987, Mai Moussa 1996, Grouzis et al. 2006). Integration of crop and trees improves soil chemical and physical properties, increases crop yield and improves household income, and also conserves soil and water for environmental protection (Boffa 1999; Bayala et al. 2012). Wezel et al. (2000) have shown that shrubs (A. senegalensis, C. acuelatum and P. reticulatum) increase soil nutrient accumulation and maintain soil fertility. Trees and shrubs reduce wind velocity and trap dust mostly if they have dense foliage (Wezel et al. 2000).

Trees and shrubs contribute to food security and combat poverty; they provide fruits, wood and fodder for animals (Boffa 2000, Nikiema 2005, Faye et al. 2011, Saidou et al. 2012). In Niger, the government has developed a strategy of reforestation and participated in a program called Farmer Managed Natural Regeneration (FMNR) in collaboration with some donors, to improve soil fertility in farmers’ fields (Abasse et al. 2013). The common tree species used to improve soil fertility are A. albida, A. senegalensis, C. acuelatum, G. senegalensis and P. reticulatum. Furthermore, farmers select trees and shrubs in their fields, in regard to the socioeconomic, ecological and cultural functions of the tree species and to increase the diversity within fields (Faye et al. 2011).

A study is needed to improve the knowledge of the contribution of various tree and shrub species on soil fertility improvement in the semi-arid sub-Saharan zone, where climatic conditions are unpredictable and agriculture provides for the main household income. The objective of the present study was to provide a thorough study of soil fertility under some tree and shrub species in farmers’ fields to show farmers and community leaders the contribution of each species in the improvement of soil fertility. Especially to:

- Analyze soil fertility under different tree species
- Compare soil fertility for tree age and distance from the tree trunk

The research questions were:

- Do woody species have variable effects on soil fertility?
- Does distance from tree trunk affect soil fertility?
- Does tree age have an impact on soil fertility?

2. LITERATURE REVIEW

2.1 Woody species and soil fertility

Woody species in a semi-arid climate form a mixture of scattered trees and shrubs (Wezel 2000; Bayala et al. 2011). Trees and shrubs are deliberately selected by farmers when they are clearing fields or when natural woodland is converted into farmland (Wezel 2000). This selection of trees and shrubs is important because of their influence on soil physical and chemical properties, on household income, increasing food security and alleviation of poverty at national level (Wezel et al. 2000; Cunningham and Abasse 2005). The multi-functional uses of species increase their diversity in farmers’ fields (Faye et al. 2011). Many studies show differences between tree crowns, based on their species and age; an individual tree whose stem diameter at 1.3 m above the ground
is less than 5 cm is considered as juvenile (Béchir 2004; Ouédraogo et al. 2005; Ouédraogo 2009; Mounyatou 2011).

Over the last twenty years, many studies have described the effect of trees on soil fertility and crop productivity in many countries of the world (Wezel, 2000; Joe 2009). The integration of trees with crops is utilized by small farmers to improve subsistence agriculture (Bonkoungou et al. 1997; Boffa 1999; Bayala et al. 2011). Trees provide fodder for livestock during the dry season. While, they represent a significant supplement for cattle, trees are stable food for small ruminants as they constitute over 70% of the dry matter of the diet during the dry season (Fall et al. 2002). Also, when associated with crop systems, trees can contribute from 10 to 30% of animal feed (Nikiema 2005). Trees and shrubs provide foods and medicinal services for the population in the dry season and even during droughts when cereals became scarce (Kalinganire et al. 2008; Faye et al. 2010; Bayala et al. 2011).

Tree-crop integration improves soil chemical and physical properties, increases soil porosity and tree litter, increases organic matter accumulation and contributes to the recycling of N and P under and near the tree trunk (Belsky et al. 1989; Vetaas 1992). Thus, woody species maintain soil moisture, influence soil water holding capacity and water infiltration (Belsky et al. 1989). In research conducted by Udawata et al. (2008a) in the Midwest region of the United States near tree buffer zones, trees improved soil porosity three to five times compared to maize soybean rotation and also improved soil stability, soil carbon and nitrogen content. Research in a semi-arid climate showed that shrubs improved soil nutrient accumulation, as evidenced by increased soil organic carbon (39%), nitrogen (38%) and phosphorus (51%) (Wezel et al. 2000; Wezel 2000). Augustine and Joseph (1992) also reported that in the natural Guinea savanna of Nigeria, soils under tree canopy have higher pH, organic carbon (OC), calcium (Ca), magnesium (Mg), potassium (K), total exchangeable bases and cation exchange capacity (CEC) than in open grassland.

Research in West Africa has shown that the presence of Acacia species increases CEC, Ca and Mg by 47%, 100% and 78% respectively, under tree crowns compared to open areas (Grouzis & Akpo 2006; Mansour et al. 2013). In southwestern Niger, Wezel et al. (2000) reported that higher concentrations of C (39%), N (38%) and P (51%) were found under some shrubs species (A. senegalensis, C. glutinosum, G. senegalensis and P. reticulatum). Also these authors found that under the same shrubs, concentration of K+ and rates of Al³⁺ and H⁺ on effective cation exchange capacity (ECEC) are increased by 22%, 44% and 55%, respectively. Kho et al. (2001) found again in Niger that the availability of N and P is more than 200% and 30% greater, respectively, under A. albida than in open areas. Research under A. albida shade shows that millet yield is multiplied by 2.5 and seed protein content under trees is higher (10.68%) than in open areas (8.10%) (Kho et al. 2001; Grouzis & Akpo 2006). Studies by Bayala et al. (2002) in Saponé, Burkina Faso, also show that mulching with Parkia paradoxa leaves increase millet yield by 120% and dry matter by 43%.

Shrubs and trees reduce wind velocity in semi-arid zones and increase deposition of top soil particles by trapping. This process in the presence of crop residues and shrubs leaves creates an “island fertile” (Wezel 2000). In addition, Cunningham and Abasse (2005) have reported in Maradi (Niger) that farmer-managed natural regeneration techniques can stabilize and reclaim degraded land. The branches and leaves placed on crusted soil or hardpan areas are mixed in the top soil by
termites and this improves soil structure. This technique can make unproductive crusted soil fertile (Cunningham and Abasse 2005).

In farmer fields, trees reduce the effect of high rainfall velocity on the ground and reduce sub-canopy solar radiation by 45 to 60% (Belsky et al. 1989) and also reduce soil temperature by 20% under the crown (Grouzis & Akpo 2006). Under shade, evapotranspiration is reduced and soil moisture is improved (Akpo 1993). Tree-crop integration increases crop yields, and the presence of trees, leaves and crop residues on the soil increases soil fauna activity and nutrient cycling which in turn improves soil fertility (Schlecht et al. 2006). Also, woody species improve overall species biodiversity. In a field survey, 79% of farmers reported that tree species increase the presence of birds and some predatory insects and reduce the use of pesticides by farmers (Cunningham and Abasse 2005). In the same way, Abass et al. (2013) show that the flowers of *P. reticulatum* produce a repulsive effect which diminish the attack of flower beetles on millet production under this species.

### 2.2 Gender and livelihoods

In most developing countries, agriculture is the source of the main household income and gender inequality, as well as unequal access to natural resources, contributes to low productivity and increases poverty (Kiptot & Franzel 2011). According to FAO (2011), agricultural production could increase by 20-30% if women had the same access to natural resources as men. In developing countries, this increase in agriculture production could improve total agricultural output by 2.5-4% and the number of the hungry be reduced by 12-17% (FAO 2011).

Most of women’s time is devoted to the family. While they produce substantial amounts of crops they have only access to a small portion of the total land (Gladwin 2002; Kiptot & Franzel 2011). Fields cultivated by women are often isolated, and in most cases it is a degraded field with low soil fertility (Kizza et al. 2012). In Niger, these kinds of fields have been given to women for fertility restoration because they cultivate leguminous crops like sesame (*Sesamum indicum*), groundnut (*Arachis hypogaea*), Bambara bean (*Vigna subterranea*) or cowpea (*Vigna unguiculata*), which are important for improving soil fertility and for nitrogen fixation.

Women in Africa spend much of their time collecting medicinal plants, firewood and fruits (Boffa 2000; Reij et al. 2009). The integration of tree species can improve soil fertility resulting in increased crop yields and thereby alleviating poverty by directly increasing income for smallholders (World Institute 2013). Also, tree species have important benefits for female farmers by increasing the availability of fodder and fuelwood for cooking obtained by pruning trees and shrubs (Kiptot & Franzel 2011), and this also reduces their workload (World Institute 2013).

Cunningham and Abasse (2005) reported that the use of Farmers Managed Natural Regeneration (FMNR) by Maradi farmers (Niger) provided farmers with 76% of the wood for cooking and 48% surplus wood for sale, and farmers can earn more than 150,000 FCFA (approximately 280$ per year). In addition, Boffa (2000) reported that many Sahel countries received export income from tree products (arabic gum from *Acacia senegal* and shea nuts from *Vitellaria paradoxa*). Also, the author found that tree use in farmers’ fields had a positive effect on the nutrition of children and diet diversity because it increases women’s income. In the same way, Reij et al. (2009) reported
that women in Zinder (Niger) who planted baobab trees increased their income (by up to $210) from the sales of tree leaves used to make sauces.

However, adopting agroforestry practices is becoming difficult for women because they do not generally have access to information and time to participate in meetings, and also have inadequate background to understand and implement technical aspects of these practices (Kiptot & Franzel 2011).

2.3 Background of land degradation and rights to tree utilization

Lack of property rights and implementation of policy on natural resource management can contribute to the degradation of natural resources (Neef 2001). In Niger, the degradation of natural resources (land and trees) started during the colonial period and became drastic in the postcolonial period (Moussa et al. 2016). In the colonial period, the government encouraged farmers to produce export crops and introduce veterinary and medical care, which increased the numbers of animals (Stickler 2012). This practice created pressure on natural resources by overgrazing and overharvesting of fuelwood. To regulate the use, all trees became government property and farmers could purchase permits to use and cut trees for wood. After independence, the Niger administration declared ownership of all trees that have an economic value, both in protected areas and on private land, and they became protected species (Neef 2001; Moussa et al. 2016). Due to the lack of rights to the use of trees and fearing to lose their fields or that their fields would become protected areas, farmers who cultivated cash crops decided to cut all young trees (Ajayi & Place 2012) to limit competition and to get more space. This deforestation decreased soil cover and crop yields and also exposed soil to erosion and degradation.

The severity of the drought of 1974 was enhanced by the scarcity of trees, resulting in loss of livestock, increased land degradation and migration (Moussa et al. 2016). This led to changes in natural resource management. To combat land degradation and to improve soil fertility for good yield production, the official policy was to initiate tree planting, provide land tenure security and rights to farmers by converting customary law to formal law (Lavigne et al. 2002; Ajayi & Place 2012). In 2004, forestry law gave tree tenure to land owners, and the local community obtained legal rights to protect and conserve natural resources (Adam et al. 2006; Stickler 2012; Moussa et al. 2016). In collaboration with some donors’ projects, the Niger government started a program of disseminating technological information and to encourage farmers to manage trees in their fields (Adam et al. 2006; Neef 2001; Ajayi & Place 2012). The Niger Independence Day became a day of planting trees throughout the country. Adoption of tree management improves soil fertility and household income and area re-greening (Haglund et al. 2011; Boffa 2000).
Figure 1. A map of Western Niger showing the study area in yellow (Source: Hiernaux & Ayantunde 2000).
3. METHODOLOGY

3.1 Description of the study area

The area in which the study was conducted is the rural town of Dantiandou, located in western Niger between 13° 24’ 45” N and 2° 45’ 23” E (Fig. 1). Dantiandou covers 500 km² and lies 75 km to the west of the capital area of Niamey. Soils are classified as Arenosol or Psammentic Paleustalf with 90% sand in horizon A (Akponikpe et al. 2014). The soils have a coarse texture and high infiltration rate, low organic carbon (~ 0.2%) and CEC (~1.2 cmolₖg⁻¹). These soils are acidic with a pH of about 5.3 and low total nitrogen (~ 0.16 g kg⁻¹) and available phosphorus content (~ 4.1 mg kg⁻¹) (Hayashi (2005), as cited in Hayashi et al. 2012).

The climate is semi-arid with unpredictable and monomodal rainfall centered in August and varying in space and time (Sivakumar 1993). Yearly average rainfall is about 550 mm. Dantiandou has two seasons: a short rainy season of 3 to 4 months (July to September) and a long dry season of 9 months (October to June). The dry season is also divided into two periods: a dry humid season (2 to 3 months) and a dry hot season (5 to 6 months).

In the town of Dantiandou, the population practices subsistence agriculture in integration with trees and shrubs. Millet is the main crop and it is cultivated generally in association with cowpea. At the edge of millet fields, farmers add some rows of sesame or sorrel. Agriculture is the main source of household income and is challenged by climatic conditions.

3.2 Study design and data collection

The research field is one hectare under parkland, and millet is the main crop. The study design was a complete randomized block with three replicates per tree species which were divided into two age classes, young and mature.

Soil samples were taken under and outside crowns of trees along transects according to cardinal points (North, South, East and West). The soil was sampled at five levels of depth at a distance of 1 and 2 m from the tree trunk for young trees (Fig. 2) and 1.5, 3, 4.5, 6, 7.5, 9, 10.5 and 12 m for old trees (Fig. 3) along the 4 transects (cardinal points). The crown radius of young trees was less than 2 m and for mature trees it ranged between 6 and 10.5 m. At each sampling location along the transect, soil cores were taken. The 4 cores from each of the four cardinal transects were mixed to form a composite sample for one point. A soil auger (4.7 cm in diameter) and sampling shovel were used for taking composites samples in December 2014.

In this study, the factors were:

a. Tree/shrub species: 4
   - *Acacia albida*,
   - *Piliostigma reticulatum*,
   - *Annona senegalensis*
   - *Combretum aculeatum*. 
b. Age: 2 classes  
   - Age 1: shrubs with crown radius less than 2 m (Fig. 2). In this case, sampling started at 1 m from trunk (under crown) and 2 m (outside crown) (*A. senegalensis*, *C. aculeatum* and *P. reticulatum*)  
   - Age 2: trees with crown radius more than 2 m (Fig. 3), sampling started at 1.5 m from trunk (under crown) and at 1.5 m intervals until outside crown (*A. albida* and *P. reticulatum*).  

c. Soil depth: samples were taken at 5 levels (Figs. 2B and 3B show cross-sectional view)  
   - 0 – 10 cm  
   - 10 – 20 cm  
   - 20 – 30 cm  
   - 30 – 40 cm  
   - 40 – 50 cm  

Figure 2. Soil sampling under young trees in 4 transects (cardinal points: East, West, North and South) at all soil depths and distances from tree trunk (A: top view and B: cross-sectional view).
3.3 Data analysis

3.3.1 Laboratory analysis

Soil samples were air dried and passed through a 2 mm sieve before chemical analysis. The soil samples were analyzed in the laboratory of the International Crops Research Institute of Semi-Arid Tropics (ICRISAT) and all the analyses were done according to Reeuwijk (1993) methods. The following parameters were analyzed: pH, organic carbon (OC), ammonium-N (NH$_4$), phosphorus (P), sodium (Na), potassium (K), calcium (Ca) and magnesium (Mg).

Soil pH was determined with a pH meter in soil samples mixed with distilled water (1:2.5). The silver-thiourea (AgTu) on 0.01M method was used for exchangeable bases extraction (Reeuwijk 1993). Atomic spectroscopy absorption was used for Ca and Mg determination, and flame spectroscopy emission was used for Na and K determination. Bray 1 method was used for phosphorus quantitative determination, HCl 0.025N and NH$_4$F 0.03N were used for extraction. The quantitative determination was done by colorimetry with molybdo-phosphate complex reduced to ascorbic acid method. The Walkley and Black method was used for organic carbon analysis. Soil organic matter was oxidized with a mixture of H$_2$SO$_4$ and K$_2$Cr$_2$O$_7$, and quantitative determination of organic carbon in the sample was achieved by extracting and titrating the remaining amount of K$_2$Cr$_2$O$_7$ with ferrous sulfate (Reeuwijk 1993). The indophenol blue method, a method that both detects NH$_4^+$ and NH$_3$ forms of N, was used for ammonium-N determination (FAO 2008). For ammonium-N extraction, 2M KCL was mixed with 1 ml of EDTA and 2 ml of
phenol-nitroprusside used as reagent, followed by 4 ml of buffered hypochlorite reagent (FAO 2008).

### 3.3.2 Statistical analysis

Data on soil properties for the four tree species were analysed with three-way ANOVA for determination of the influence of tree species, crown and soil depth on soil nutrient distribution. One-way ANOVA was used for determination of tree age effect and impact of distance of sampling from tree trunk on soil fertility.

For tree age analysis, *P. reticulatum* was chosen because it was the only species that had both young and mature trees. For distance from tree trunk analysis, *A. albida* was chosen because it was the only species that had a big crown.

The Student-Newman-Keuls (SNK) test was used to compare means for species, soil depth, crown, age, and distance from tree trunk classification at the 95% confidence level. SAS 9.4 was used for all statistical analyses (SAS 2014).

Excel was used for making graphics of variables and factors, where statistically significant differences were found, for visual presentation and evaluation.

### 4. RESULTS

#### 4.1 Influence of tree species on soil fertility

In all cases the ANOVA model significantly explained the variation of the measured soil variables in the field (Table 1).

Table 1. F-values form a three-way ANOVA analysis for Dantiandou site (Niger). (df = degrees of freedom, OC = organic carbon, NH₄ = ammonium-N, P = phosphorus, Na = sodium, K = potassium, Ca = calcium, Mg = magnesium, ns = not significant, *p*<0.05, **p*<0.01, ***p*<0.001).

<table>
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<th>Source</th>
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<th>OC</th>
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<th>P</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
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<td>39</td>
<td>2.42***</td>
<td>7.70***</td>
<td>2.03**</td>
<td>1.69*</td>
<td>8.47***</td>
<td>4.44***</td>
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<td>3.96**</td>
<td>16.60***</td>
<td>77.10***</td>
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<td>13.46***</td>
</tr>
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<tr>
<td>Soil depth</td>
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</table>

Three-way ANOVA results showed that there were significant differences between species for all the parameters measured (pH, OC, NH₄, Na, K, Ca and Mg). Tree crown had a significant effect only on Ca, and soil depth had a significant effect on all chemical properties analyzed except for
P. The interaction between species and crown was significant for pH, Na and Ca and the interaction between species and soil depth was only significant for OC.

4.1.1 pH

The soil beneath *P. reticulatum* had a higher pH than for the other tree species, except for *A. senegalensis* (Fig. 4), but *C. aculeatum* displayed a lower pH than all other species. The pH varied significantly between soil depth classes (Table 1), where pH was higher near the surface than below 20 cm depth (Fig. 5).

The interaction between species and crown was also significant (Table 1); the pH was higher under the crown of *C. aculeatum* and *P. reticulatum* than outside crown. The reverse was observed with *A. albida* (Fig. 6).

![Figure 4. Soil pH under the four tree species. Each column represents the mean value of pH for all soil depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences (p<0.05) between species.](image-url)
Figure 5. Soil pH for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and different column letters show significant differences (p<0.05).

Figure 6. Soil pH under crown positions (UC = under crown and OC = open crown) for each species at all soil depths. n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences (p<0.05) between OC and UC for each species.
4.1.2 Organic Carbon (OC)

The soil OC was significantly different between species (Table 1). *A. albida* had the highest mean (0.14%) of soil organic matter and *C. aculeatum* and *A. senegalensis* had the lowest mean (Fig. 7). As for pH, the percentage of OC decreased with soil depth. The top layer (0-10 cm) had the highest value and the lowest values were found below 20 cm (Fig. 8).

Figure 7. Soil organic carbon (OC) under the four tree species. Each column represents the mean value of OC for all depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences (p<0.05) between species.

![Figure 7](image_url)

Figure 8. Soil organic carbon (OC) for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and different letters show significant differences (p<0.05).

![Figure 8](image_url)
The interaction between species and soil depth was significant for soil OC (Table 1) and the change with soil depth evolved in the same manner for each species as described above, except for *P. reticulatum* (Fig. 9).

![Figure 9](image.png)

Figure 9. Soil organic carbon (OC) for the five soil depths under each tree species. Each mean includes values for crowns positions and n represents the number of observation of each mean. The vertical bars show standard deviation and different letters indicate significant differences between soil depth for each species.

### 4.1.3 Ammonium-N (*NH₄*)

![Figure 10](image.png)

Figure 10. Soil *NH₄* under the four tree species. Each column represents the mean value of *NH₄* for all soil depths combined and crown positions. n represents the number of observations for each mean. The vertical bars show standard deviation and different letters illustrate significant differences between species (p<0.05).
There was a significant difference between species for soil ammonium-N (Table 1). Mean ammonium-N content in soils beneath *P. reticulatum* was higher than for *C. aculeatum* (Fig. 10). Also, NH$_4$ decreased with soil depth and the top layer (0-10 cm) had a higher mean than the other soil depth classes (Fig. 11).

![Figure 11. Soil NH$_4$ for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples at each soil depth. The horizontal bars show standard deviation and different column letters show significant differences (p<0.05).](image)

*4.1.4 Phosphorus (P)*

![Figure 12. Soil P under the four tree species. Each column represents the mean value of P for all soil depths and crown positions, and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters illustrate significant differences between species (p<0.05).](image)
The soil phosphorus was only significantly different between tree species (Table 1). *C. aculeatum* had a lower mean value than the other species (Fig. 12).

### 4.1.5 Sodium (Na)

The results from the three-way ANOVA of Na (Table 1) show that there was a significant difference for species and soil depth. *P. reticulatum* had a higher mean than other species and *A. senegalensis* had the lowest mean (Fig. 13). The amount of Na changed with soil depth and the top 20 cm had a higher content than other soil depth classes (Fig. 14). In addition, the deepest soil depth class (40-50 cm) had less Na than other classes.

The interaction between species and crown showed that there was a significant difference between species under and outside the crown (Table 1). The mean of Na under the crown of *P. reticulatum* was higher than outside the crown, but the reverse was observed with *A. albida* (Fig. 15).

![Figure 13. Soil Na under the four tree species. Each column represents the mean value of Na for all depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters illustrate significant differences between species (p<0.05).](image-url)
4.1.6 Potassium (K)

In the same way as for some other soil parameters, the value of soil K was significantly different between species and soil depth classes (Table 1). There was no significant difference between *A. senegalensis*, *P. reticulatum* and *A. albida* but *C. aculeatum* had a lower mean of K than the other species (Fig. 16). The top 20 cm of the soil were richer in K than below 20 cm (Fig. 17). In addition, the lowest soil depth class (40-50 cm) had less K than other soil depth classes.
4.1.7 Calcium (Ca)

With Ca, there was significant variation between tree species and soil depths (Table 1). *A. albida* had a higher mean than other species except for *P. reticulatum*. *A. senegalensis* had a lowest mean than *A. albida* and *P. reticulatum* (Fig. 18). The top 20 cm of the soil had a higher mean value of Ca than other soil depths, and below 20 cm all depth classes were successively lower than the next one above (Fig. 19).
The interaction between species and crown also showed that the amount of Ca was higher under than outside the crown for *P. reticulatum* and *C. aculeatum* but the reverse was found with *A. albida* (Fig. 20).

**Figure 18.** Soil Ca under the four tree species. Each column represents the mean value of Ca for all depths and crown positions, and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences between species (p<0.05).

**Figure 19.** Soil Ca for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and letters show significant differences (p<0.05).
Figure 20. Soil Ca under crown positions (UC = under crown and OC = open crown) for each species at all soil depths. n represents the number of observations for each mean. The vertical bars show standard deviation and letters show significant differences (p<0.05) between OC and UC for each species.

4.1.8 Magnesium (Mg)

With Mg, there was significant variation between species and soil depths (Table 1). A. albida had a higher mean of Mg than other species except for P. reticulatum. Also, A. senegalensis had the lowest mean (Fig. 21). Mg also significantly decreased with soil depth except below 30 cm (Fig. 22).

Figure 21. Soil Mg under the four tree species. Each column represents the mean value of Mg for all depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviations and different letters illustrate significant differences between species (p<0.05).
Figure 22. Soil Mg for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples at each soil depth. The horizontal bars show standard deviations and different letters show significant differences (p<0.05).

4.2 Effect of soil sampling distance from A. albida tree trunk on soil parameters

The analysis of one-way ANOVA shows that there was significant variation with distance for only P (Table 2).

Table 2. F-value from one-way ANOVA analysis results for distance from A. albida tree trunk (df = degrees of freedom, OC = organic carbon, NH$_4$ = ammonium-N, P = phosphorus, Na = sodium, K = potassium, Ca = calcium, Mg = magnesium, ns = not significant, ***p<0.0001).

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>pH</th>
<th>OC</th>
<th>NH$_4$</th>
<th>P</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model</td>
<td>7</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>5.93***</td>
<td>ns</td>
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<td>ns</td>
<td>ns</td>
</tr>
<tr>
<td>Distance</td>
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<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>3.70***</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

Soil P decreased with increasing distance from A. albida tree trunk. Close to the tree trunk (1.5 and 3 m) the P value was higher than outside crown (9, 10.5 and 12 m) (Fig. 23).
Figure 23. Soil P under *A. albida* for distance from tree trunk (*n* = number of soil samples). Vertical bars show standard deviation of means and different letters show significant differences between distances.

### 4.3 Impact of *P. reticulatum* tree age on soil parameters

The one-way ANOVA analysis showed that there was only a significant difference between ages for pH and P.

**Table 3.** F-value from One-way ANOVA analysis results for *P. reticulatum* tree age (df = degrees of freedom, OC = organic carbon, NH$_4$ = ammonium-N, P = phosphorus, Na = sodium, K = potassium, Ca = calcium, Mg = magnesium, ns = not significant, **p<0.001, ***p<0.0001).

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>pH</th>
<th>OC</th>
<th>NH$_4$</th>
<th>P</th>
<th>Na</th>
<th>K</th>
<th>Ca</th>
<th>Mg</th>
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</thead>
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<td>45.66***</td>
<td>ns</td>
<td>ns</td>
<td>11.91**</td>
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<td>ns</td>
</tr>
<tr>
<td>Ages</td>
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<td>41.89***</td>
<td>ns</td>
<td>ns</td>
<td>11.17**</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
<td>ns</td>
</tr>
</tbody>
</table>

The pH was significantly different between age classes and the mature trees had a higher soil pH than young trees of *P. reticulatum*. Also for P, the mean was higher beneath mature trees than young trees (Fig. 24).
5. DISCUSSION

Tree species influenced differently the distribution of soil nutrients in the present study. Lower pH and a higher concentration of elements were generally found under tree crowns rather than outside crowns, except for A. albida. Under this species, concentrations of pH, Na and Ca were lower under crowns than outside crowns. A. albida has a reverse cycle compared to other species (A. senegalensis, C. aculeatum and P. reticulatum): in the rainy season, this species does not produce more foliage (Jonsson et al. 1999). Under A. albida trees, there is an accumulation of both bark and leaf litter. According to Zinke (1962), the bark is very acid and low in bases, whereas leaf litter is high in bases and nitrogen content (Zinke 1962). Due to the fact that A. albida is a big tree, it produces more bark litter. Therefore, the acidity of bark litter can reduce the concentrations of Na and Ca under the A. albida crown (Zinke 1962).

The influence of the tree crown decreases with increasing distance from the tree trunk because of the accumulation of organic matter near the tree trunk. Leaves of trees are rich in carbon and the accumulation of leaf litter under trees increases microbiological activities and soil organic matter (Isaac et al. 2011; Mansour et al. 2013). The mineralization of soil OC under trees and the root symbiosis with mycorrhizal fungi increase the concentration of soil nutrients under tree crowns (Mansour et al. 2013). The same result was reported by Vetaas (1992) in dry savannas. According to this author, the interaction between trees, the contribution of symbiotic micro-organisms, and understory plants increase the nutrient recycling near the tree trunk. Also, there is some attraction of animals who can contribute nutrients by manure (Vetaas 1992). The higher concentration of soil nutrients near the tree trunk is therefore due to the accumulation of organic matter near the tree trunk, positively influenced by a cooler microclimate and micro-faunal activity (Buerkert et al. 1989; Vetaas 1992). This phenomenon diminishes when the input of organic matter is reduced with increasing distance from tree trunk (Vetaas 1992; Mansour et al. 2013). As a result, many researchers investigating the influence of trees on soil fertility considered three zones: the first
zone is the radius of the crown in which there is a relatively high concentration of bark and leaf litter, the second zone is the part under the crown which has less leaf litter, and the third zone is outside the crown where there is no litter accumulation (Zinke 1962). Rhoades (1997) reported that the soil near the tree trunk is richer in nutrients because of the leaching of dust from the leaf surface, scraps of dead insects, and nutrients from the tree trunk carried by flowing water or rainfall which concentrates at the tree trunk base. Also, Wezel et al. (2000) has shown that in the presence of shrubs, soil nutrients (N, P and K) were significantly higher within 50 cm radius from the tree trunk and became less outside 150 cm radius. Zinke & Crocker (1962) showed that for old Sequoia giganteum with 6 to 9 m of crown diameter, the influence zone can reach 3 m from the tree trunk, which was similar to our result of A. albida with a crown diameter between 6 to 10.5 m.

In the same way, tree crown size and soil nutrients increase with tree age because they produce and accumulate more organic matter than young trees. The work of Zhong & Zhao (2003) in the north of China with Caragana microphylla in a sequence age of 0, 5, 13 and 28 years old showed that soil carbon and nitrogen accumulation increases with age of plantation. In India, under a sequence of Prosopis juliflora plantation of ages 0, 5, 7 and 30 years, Bhojvaid & Timmer (1998) showed that the soil fertility increases with the plantation age. In their study, the first years (0 to 5 years) were characterized by high soil temperature and initial changes in soil properties (Bhojvaid & Timmer 1998). The transitional phase with closure of the tree canopy started between 5 to 7 years; in this period litter production, nutrient cycling and soil fertility increased, and the tree root system expanded. The last phase was fallow enrichment in which there was a stabilization of soil development with increased vertical soil formation with time (Bhojvaid & Timmer 1998).

Also, Augustine and Joseph (1992) have shown that trees with more than 7 m of crown diameter have higher OC, CEC, Ca, Mg and P under their canopy than trees with less than 7 m of crown diameter. The effect of tree age reduces attack on crops by insects, as showed by Abass et al. (2013) in the region of Aguié (Niger). The authors found that, under three age groups of P. reticulatum (0-2 years, 3-5 years and more than 6 years), the old trees (more than 6 years) produced more flowers than the young trees. The flowers produce a repulsive odor on flower beetles which attack the crops, thus resulting in increased yield under old trees compared to young trees (Abass et al. 2013).

In the present study, soil nutrient concentrations decreased with increasing soil depth irrespective of tree species, distance from the tree trunk or tree age. The organic matter was also concentrated near the soil surface between 0 and 20 cm but below this layer nutrient concentrations changed. Bhojvaid & Timmer (1998) got a similar result under Prosopis juliflora. Soil samples taken at 15, 30, 60, 90 and 135 cm depth showed that the level of N and C declined with depth after 30 cm. This was due to high litter accumulation and decomposition and higher fine root turnover near the soil surface which increased nutrient recycling (Bhojvaid & Timmer 1998). Zhong & Zhao (2003) also got similar results for Caragana microphylla in the north of China. The samples were taken at two depths (0-5 cm and 5-20 cm) in an age sequence of 0, 5, 13, 21 and 28 years. C and N decreased with soil depth for all the ages because tree establishment and development initially influenced mostly soil properties in the surface horizon, starting with an increase in soil organic matter accumulation and decomposition. In order to explain the vertical distribution of soil nutrients Jobbagy and Jackson (2001) took soil samples at 5 depths (0-20, 20-40, 40-60, 60-80 and 80-100 cm) and found that the biological cycling by plants and trees increased the movement of
the most important nutrients (N, P and K). Some nutrients are transported aboveground by trees and plants, and recycling in the topsoil mixes nutrients in leaf litter and those brought by rainfall (Jobbagy and Jackson 2001). This phenomenon increases the nutrient accumulation in the soil surface (Jobbagy and Jackson 2001). In addition, Ekelund et al. (2001) measured the numbers and biomass of protozoa, bacteria and fungi at different depths (1.5-122.5 cm). They found a general decrease of biomass for all the groups with increasing soil depth. This was because the organic matter and micro-organism activities were more concentrated in the top soil and this increased the nutrient content in the shallowest more than in the deepest soil profile (Ekelund et al. 2001).

6. CONCLUSION

Woody species are important for the restoration of soil fertility, particularly in a semi-arid zone like in Niger where the low soil fertility is the main barrier to crop production. The tree species improve soil fertility in different ways and they can be integrated into crop production and soil restoration. The nutrients are more concentrated near the tree trunk and the age of trees increases their accumulation over time. A recommendation for soil fertility management and soil restoration is to sensitize farmers to maintain more mature trees in their fields and to put more crops near the tree trunks. However, further research can be done in the same way to explain better the influence of tree age and distance from tree trunk on soil fertility improvement.
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