UNITED NATIONS UNIVERSITY
UNU-LRT

**Land Restoration Training Programme**
***Keldnaholt, 112 Reykjavik, Iceland***

***Final project 2016***

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

**Mariama Boubou Diallo Oumarou**
National Institute of Agronomic Research in Niger (INRAN)
Departement of Natural Resource Management (AGRN)
Box: 412 Niamey-Niger
*mariama.diallo01@gmail.com*

**Supervisor**
Úlfur Óskarsson
Agricultural University of Iceland (AUI)
*ulfur@lbhi.is*

## 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.

This paper should be cited as:
Oumarou M B D (2016) Soil fertility under four tree species in the semi-arid climate of Niger. United Nations University Land Restoration Training Programme [final project]
http://www.unulrt.is/static/fellows/document/Oumarou2016.pdf

# TABLE OF CONTENTS

## 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 acuelatum*, *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 $Al^{3+}$ 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).

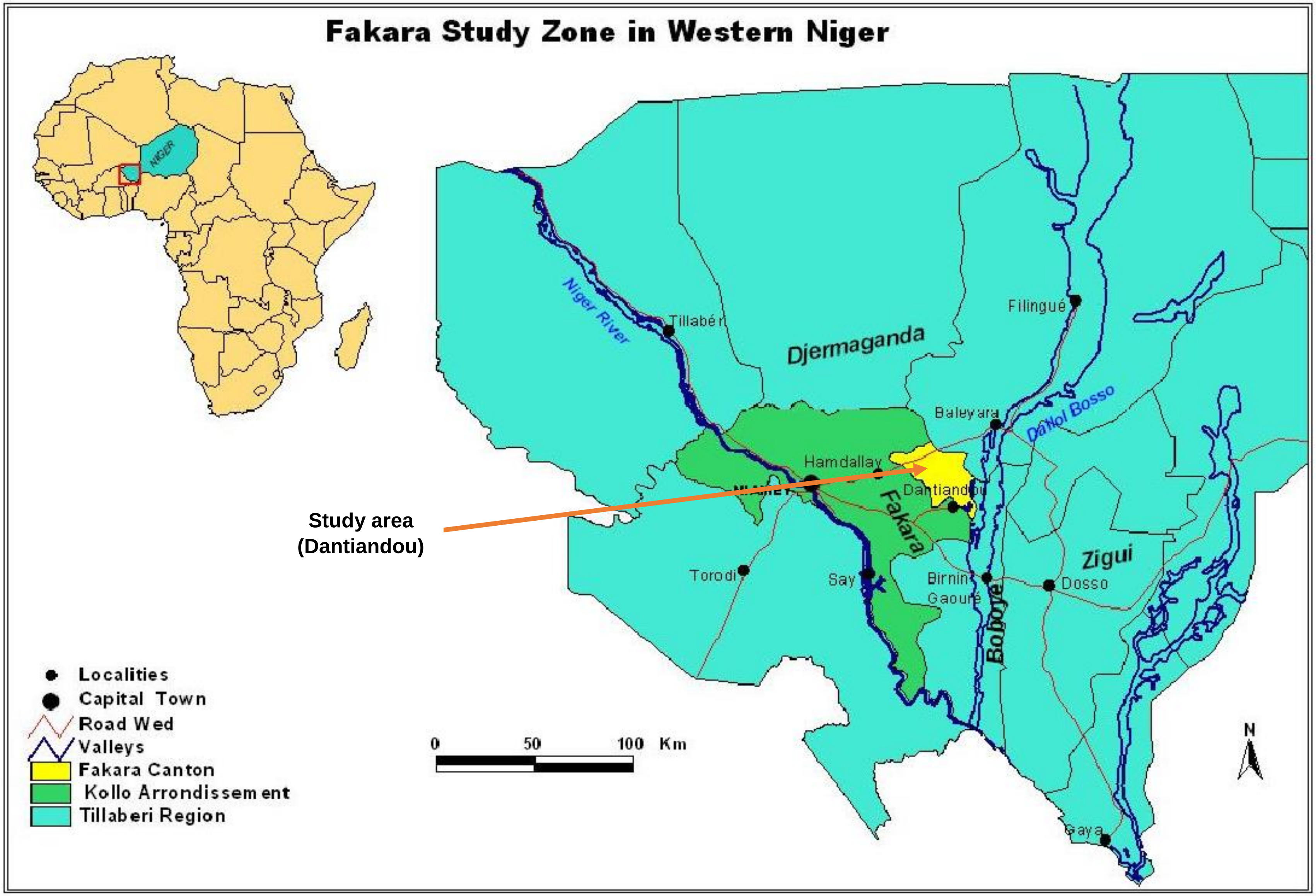


Figure 1. A map of Western Niger showing the study area in yellow (Source: Hiernaux & Ayantunde 2000).

# 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$^o$ 24' 45" N and 2$^o$ 45' 23" E (Fig. 1). Dantiandou covers 500 km$^2$ 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 $cmol_c$ $kg^{-1}$). 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

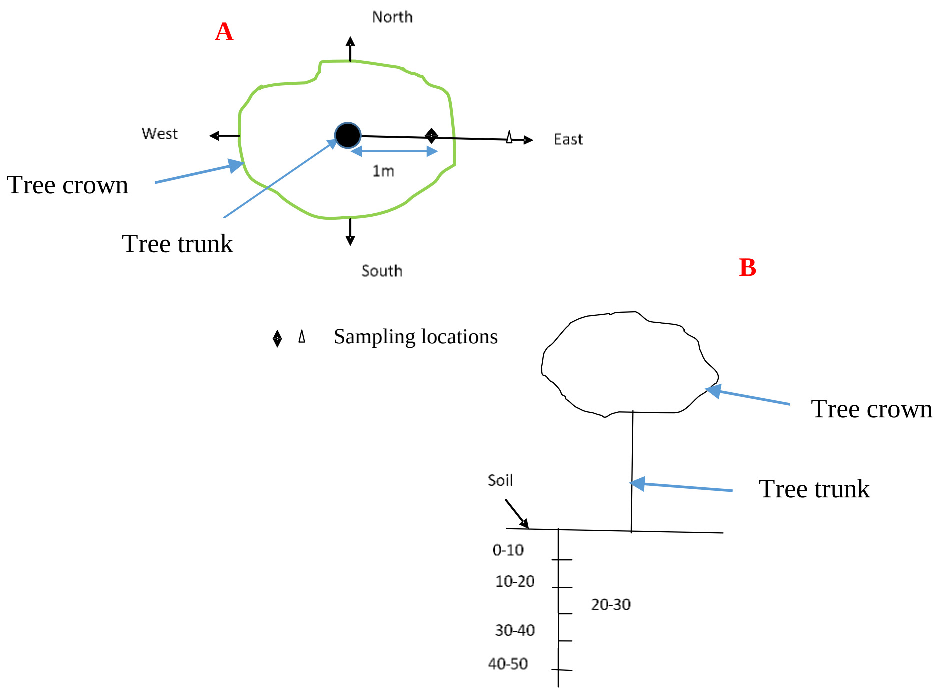


Figure 2. Soil sampling under young trees in 4 transects (cardinal points: East, West, North and South) at all soil depths and distances from tree trunk (A: top view and B: cross-sectional view).

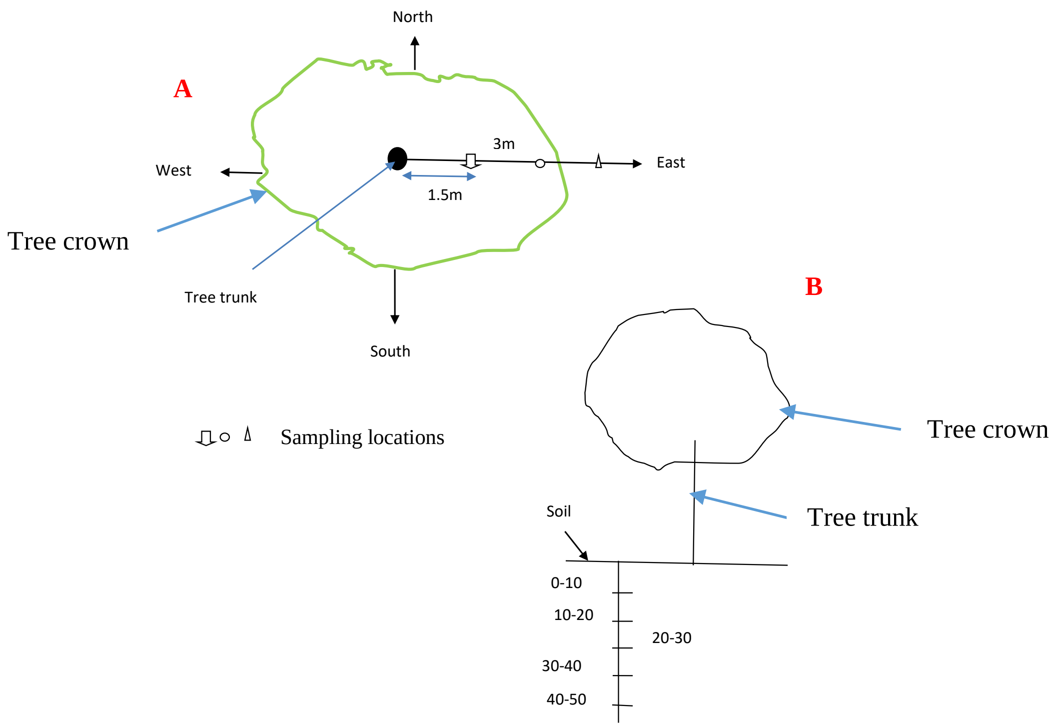


Figure 3. Soil sampling under mature trees in 4 transects (cardinal points: East, West, North and South) at all soil depths and distances from tree trunk (A: top view and B: cross-sectional view).

## 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 $NH_4F$ 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 $H_2SO_4$ and $K_2Cr_2O_7$, and quantitative determination of organic carbon in the sample was achieved by extracting and titrating the remaining amount of $K_2Cr_2O_7$ 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 specie 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% of 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, $NH_4$ = ammonium-N, P = phosphorus, Na = sodium, K = potassium, Ca = calcium, Mg = magnesium, ns = not significant, *p<0.05, **p<0.01, ***p<0.001).

| **Source** | **df** | **pH** | **OC** | **$NH_4$** | **P** | **Na** | **K** | **Ca** | **Mg** |
|---|---|---|---|---|---|---|---|---|---|
| Model | 39 | 2.42*** | 7.70*** | 2.03** | 1.69* | 8.47*** | 4.44*** | 3.80*** | 3.73*** |
| Species | 3 | 7.57*** | 9.69*** | 3.96** | 16.60*** | 77.10*** | 22.41*** | 10.00*** | 13.46*** |
| Crown | 1 | ns | ns | ns | ns | ns | ns | 4.26* | ns |
| Soil depth | 4 | 5.49*** | 20.56*** | 4.22** | ns | 8.92*** | 14.49*** | 13.63*** | 12.84*** |
| Species*Crown | 3 | 9.48*** | ns | ns | ns | 5.12** | ns | 5.30** | ns |
| Species*Soil depth | 12 | ns | 3.35*** | ns | ns | ns | ns | ns | ns |
| Crown*Soil depth | 4 | ns | ns | ns | ns | ns | ns | ns | ns |
| Species*Crown*Soil depth | 12 | ns | ns | ns | ns | ns | ns | ns | ns |

Three-way ANOVA results showed that there were significant differences between species for all the parameters measured (pH, OC, $NH_4$, 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).

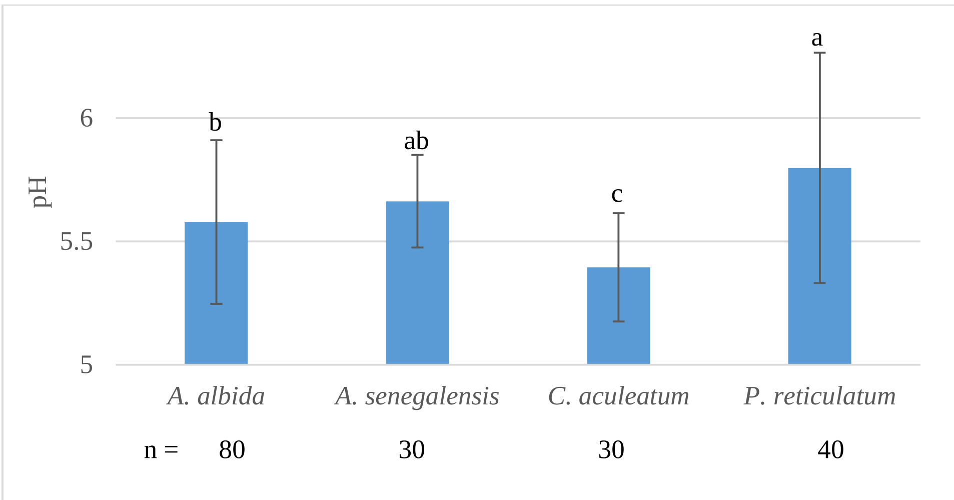


Figure 4. Soil pH under the four tree species. Each column represents the mean value of pH for all soil depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences ($p<0.05$) between species.

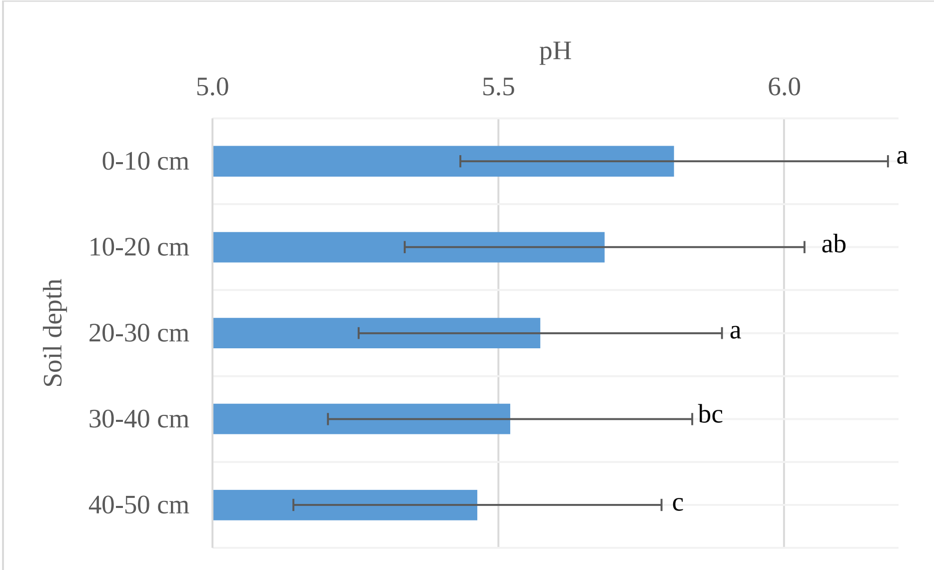


Figure 5. Soil pH for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and different column letters show significant differences (p<0.05).

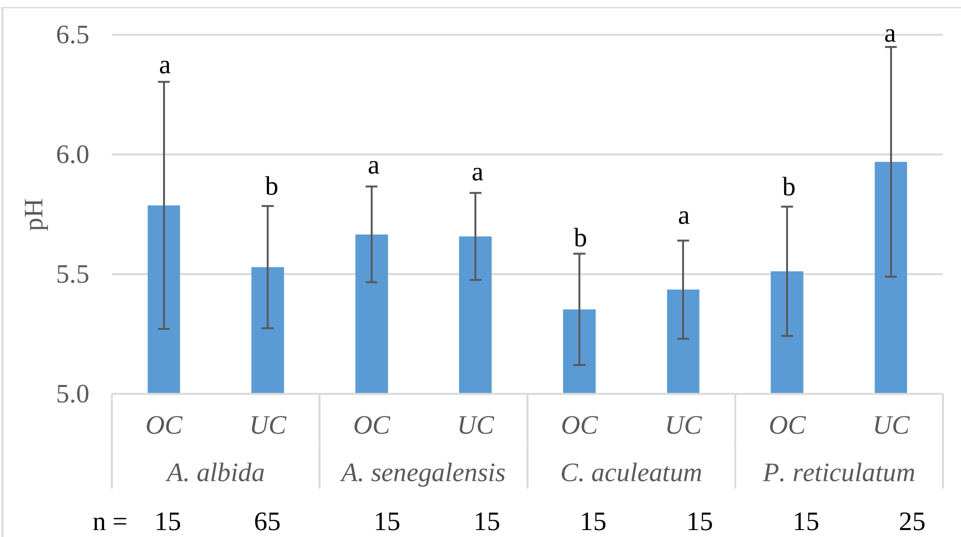


Figure 6. Soil pH under crown positions (UC = under crown and OC = open crown) for each species at all soil depths. n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences (p<0.05) between OC and UC for each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

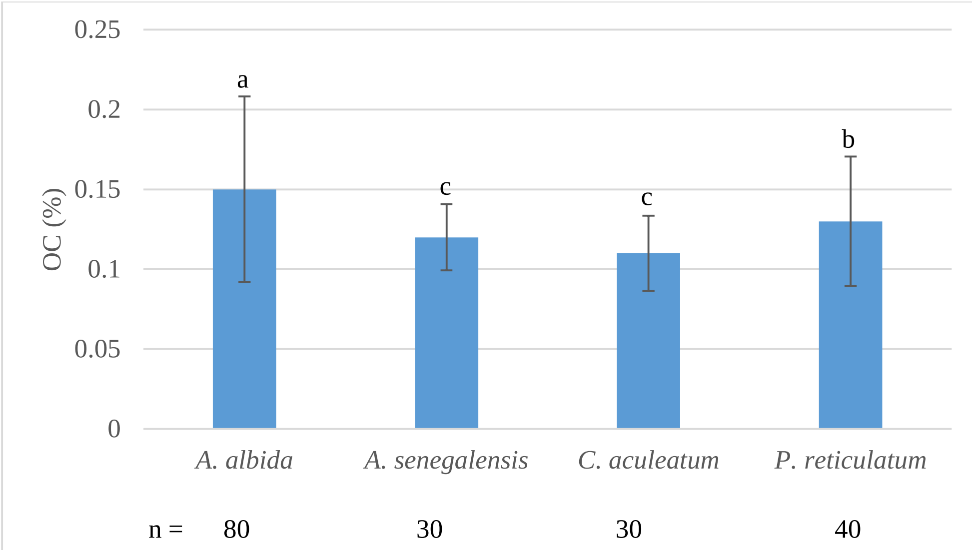


Figure 7. Soil organic carbon (OC) under the four tree species. Each column represents the mean value of OC for all depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences ($p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

### *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).

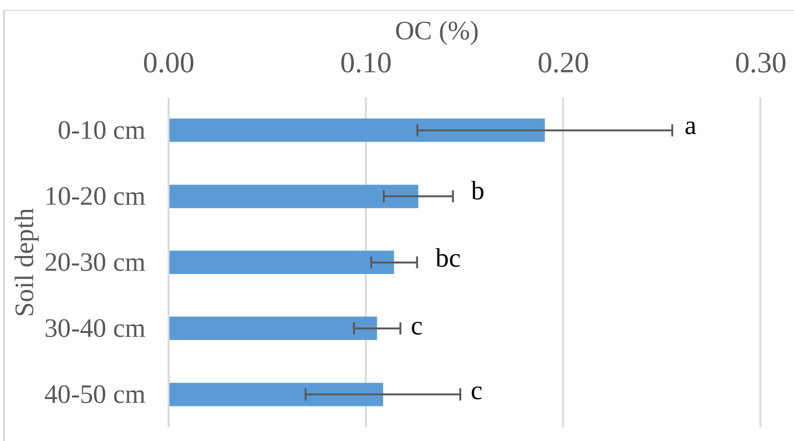


Figure 8. Soil organic carbon (OC) for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and different letters show significant differences ($p<0.05$).

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).

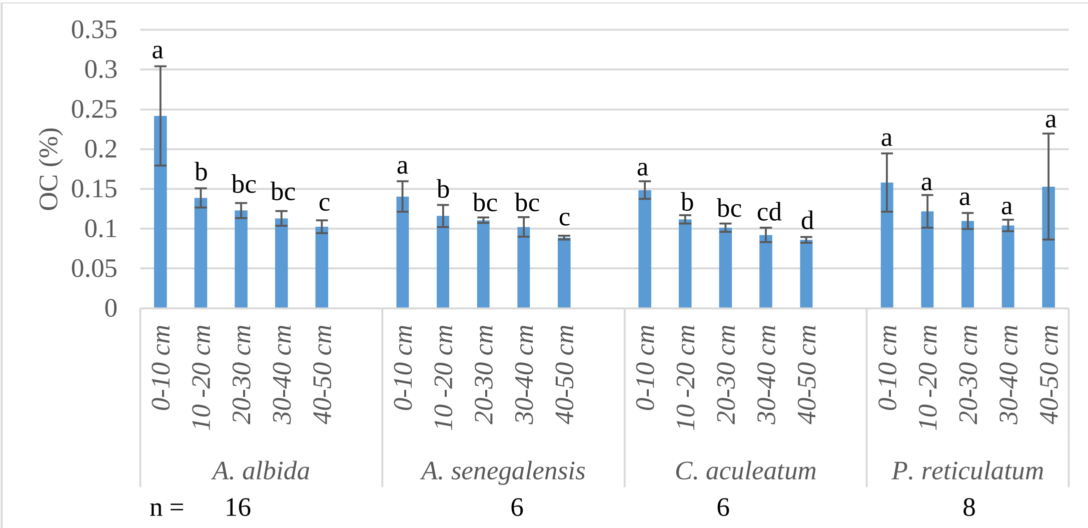


Figure 9. Soil organic carbon (OC) for the five soil depths under each tree species. Each mean includes values for crowns positions and n represents the number of observation of each mean. The vertical bars show standard deviation and different letters indicate significant differences between soil depth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

### *4.1.3 Ammonium-N (NH$_4$)*

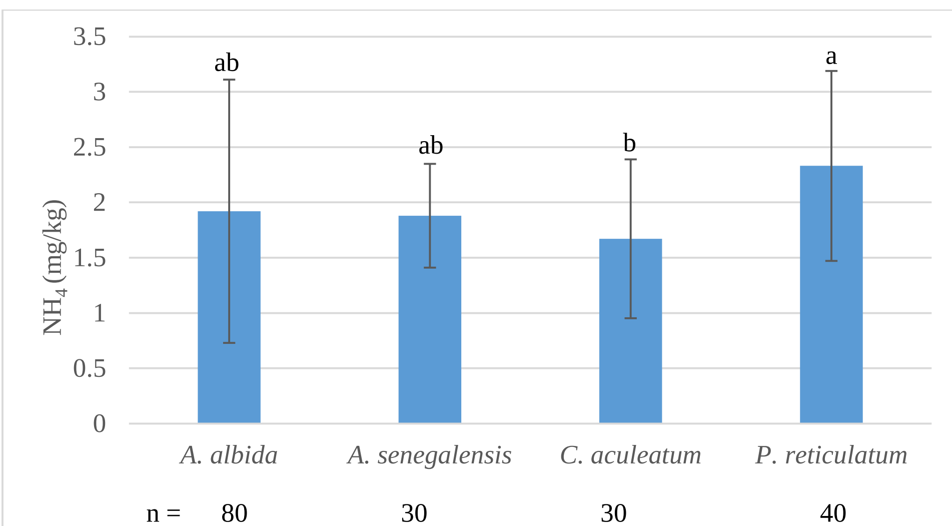


Figure 10. Soil NH$_4$ under the four tree species. Each column represents the mean value of NH$_4$ for all soil depths combined and crown positions. n represents the number of observations for each mean. The vertical bars show standard deviation and different letters illustrate significant differences 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).

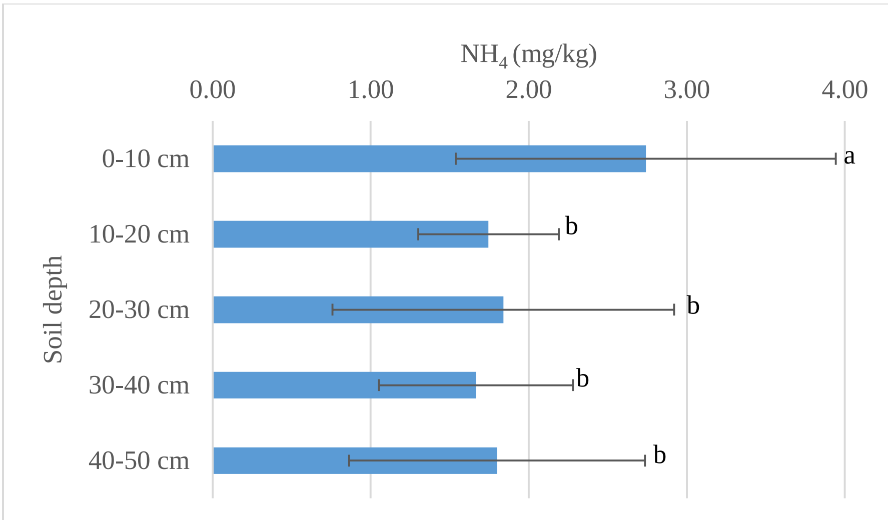


Figure 11. Soil $NH_4$ for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples at each soil depth. The horizontal bars show standard deviation and different column letters show significant differences ($p<0.05$).

### *4.1.4 Phosphorus (P)*

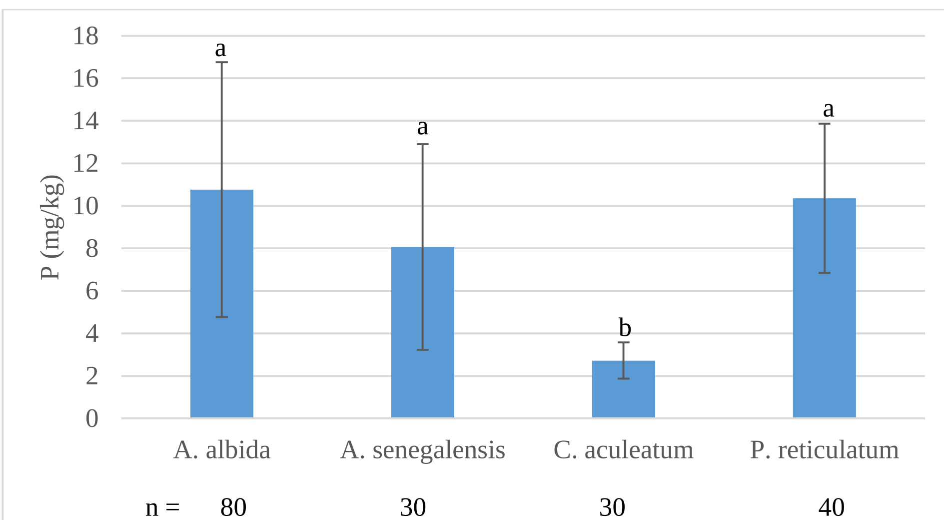


Figure 12. Soil P under the four tree species. Each column represents the mean value of P for all soil depths and crown positions, and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters illustrate significant differences between species ($p<0.05$).

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).

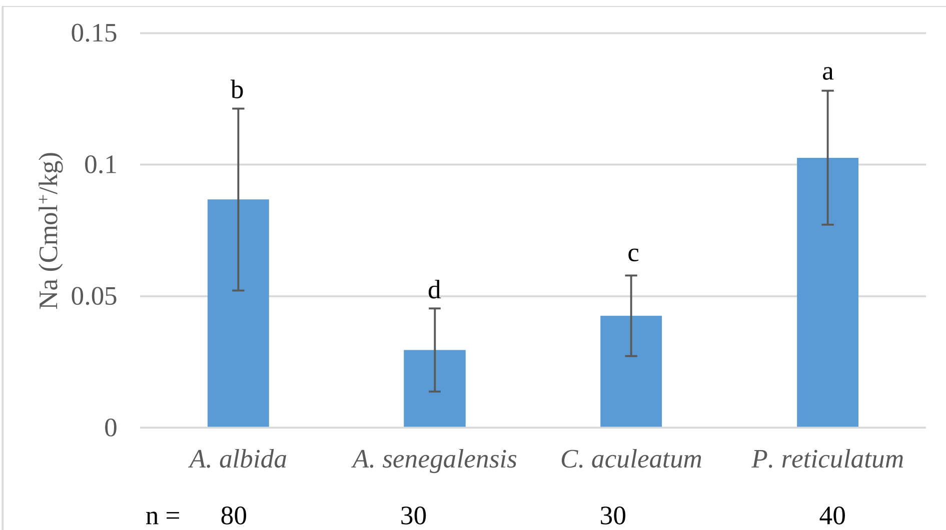


Figure 13. Soil Na under the four tree species. Each column represents the mean value of Na for all depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters illustrate significant differences between species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

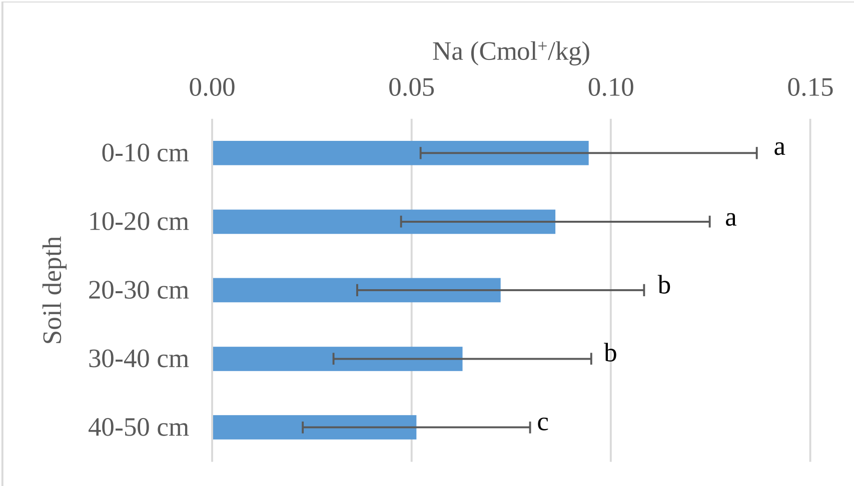


Figure 14. Soil Na for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and different letters show significant differences ($p<0.05$).

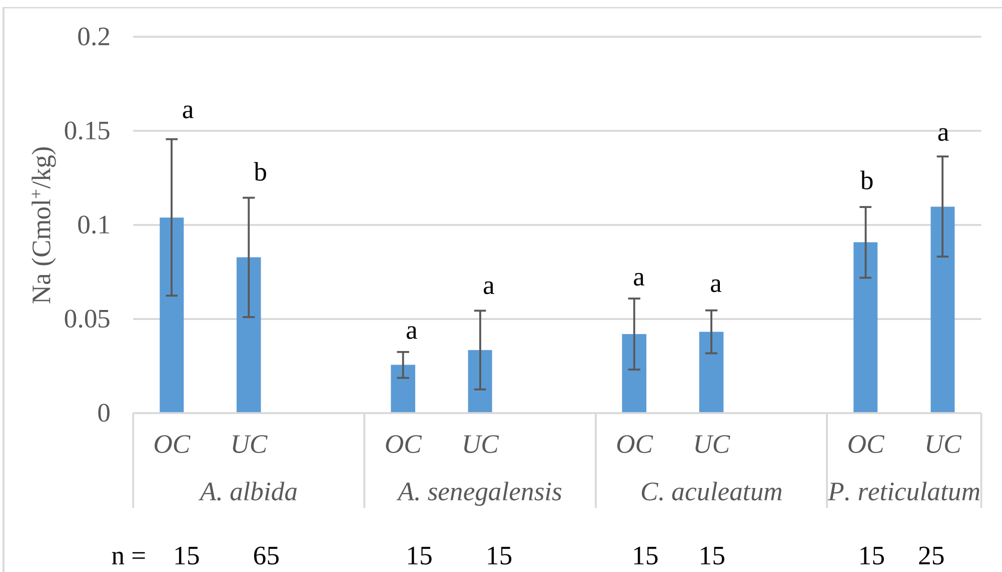


Figure 15. Soil Na under crown positions (UC = under crown and OC = open crown) for each species at all soil depths and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters show significant differences ($p<0.05$) between OC and UC for each species.

### *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.

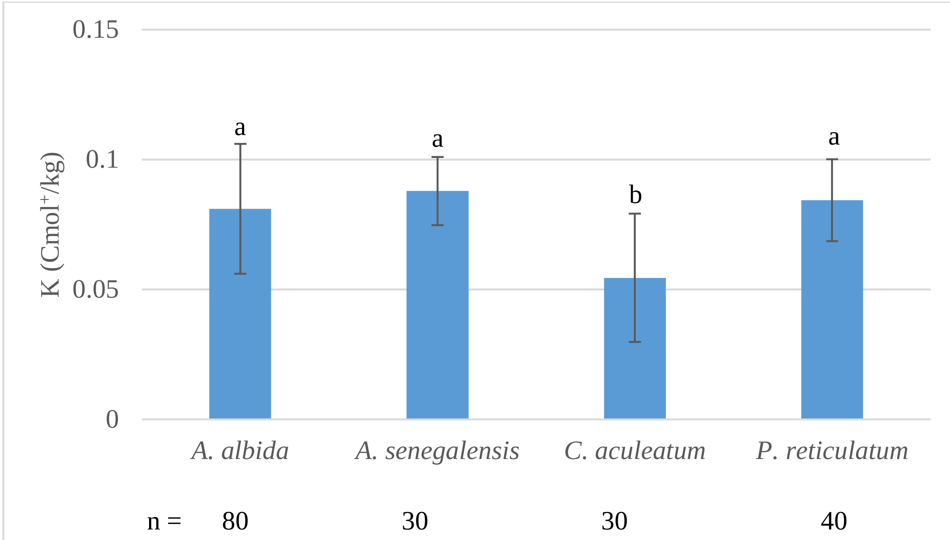


Figure 16. Soil K under the four tree species. Each column represents the mean value of K for all soil depths and crown positions. n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences between species ($p<0.05$).

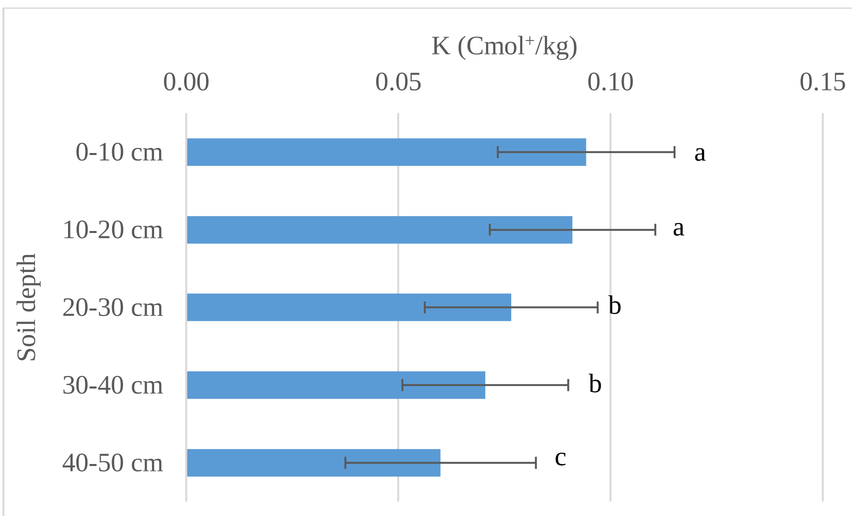


Figure 17. Soil K for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and different letters show significant differences ($p<0.05$).

### *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).

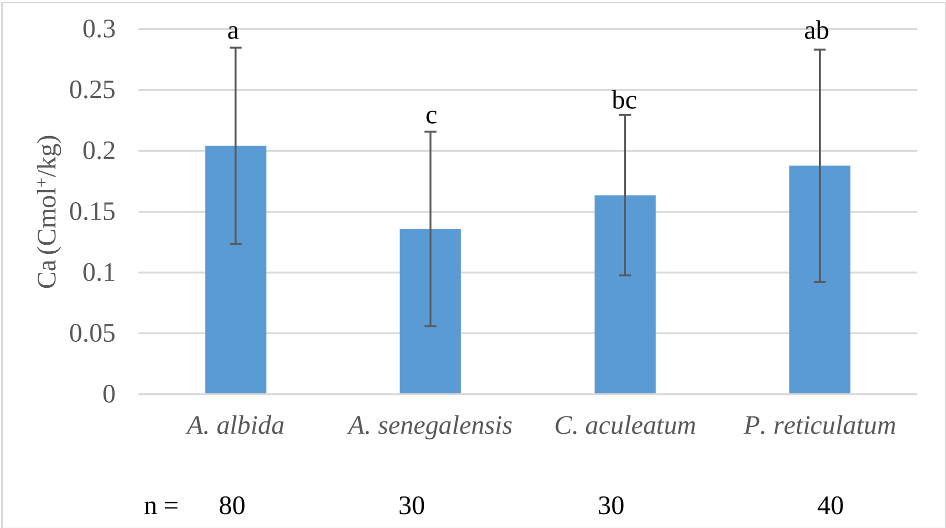


Figure 18. Soil Ca under the four tree species. Each column represents the mean value of Ca for all depths and crown positions, and n represents the number of observations for each mean. The vertical bars show standard deviation and different letters indicate significant differences between species ($p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

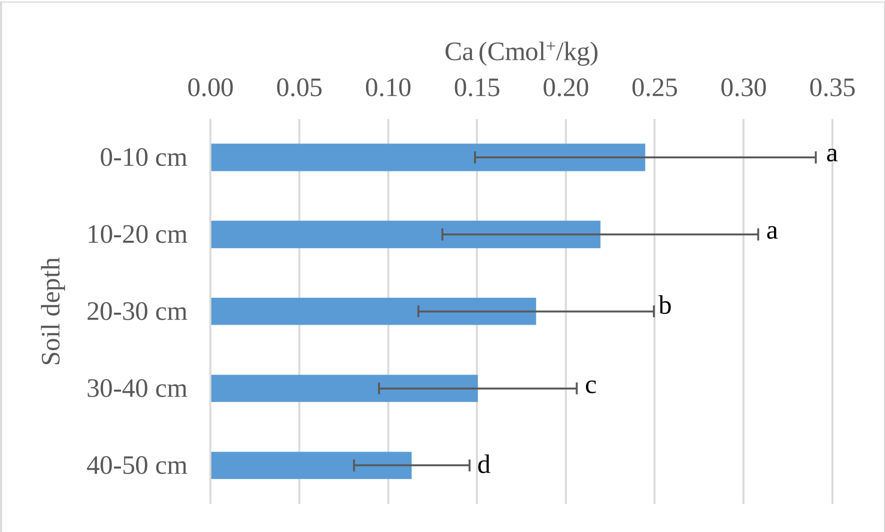


Figure 19. Soil Ca for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples behind each soil depth. The horizontal bars show standard deviation and letters show significant differences ($p<0.05$).

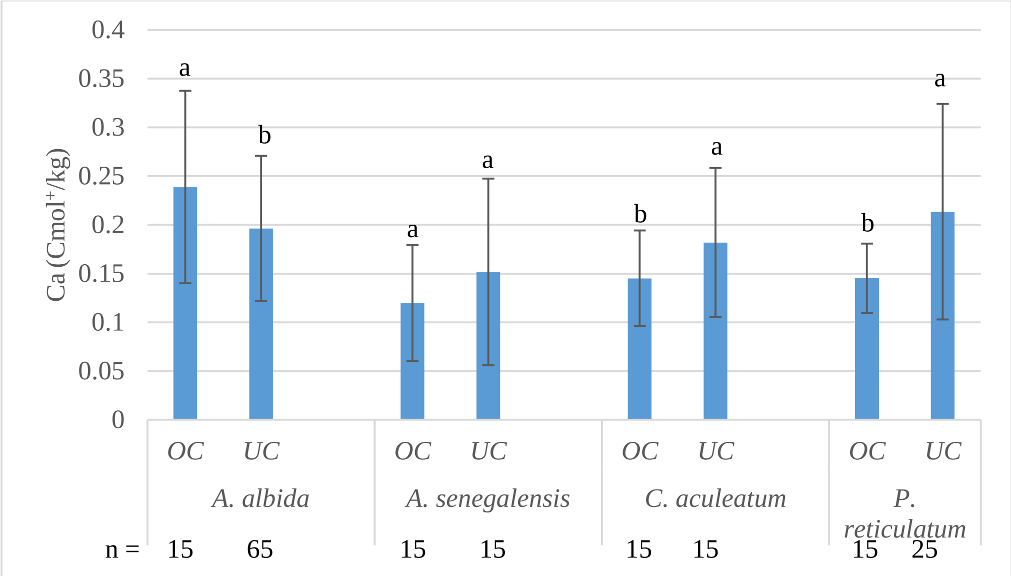


Figure 20. Soil Ca under crown positions (UC = under crown and OC = open crown) for each species at all soil depths. n represents the number of observations for each mean. The vertical bars show standard deviation and letters show significant differences ($p<0.05$) between OC and UC for each species.

### *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).

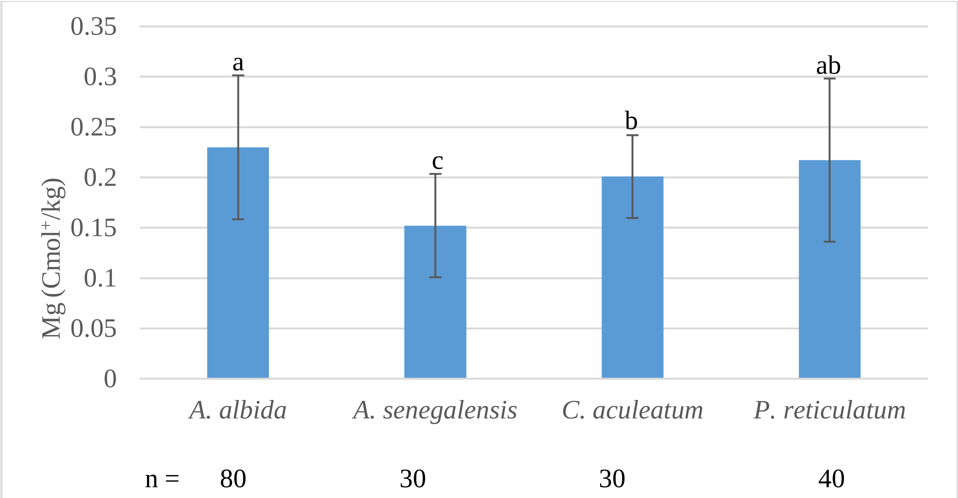


Figure 21. Soil Mg under the four tree species. Each column represents the mean value of Mg for all depths and crown positions and n represents the number of observations for each mean. The vertical bars show standard deviations and different letters illustrate significant differences between species ($p<0.05$).

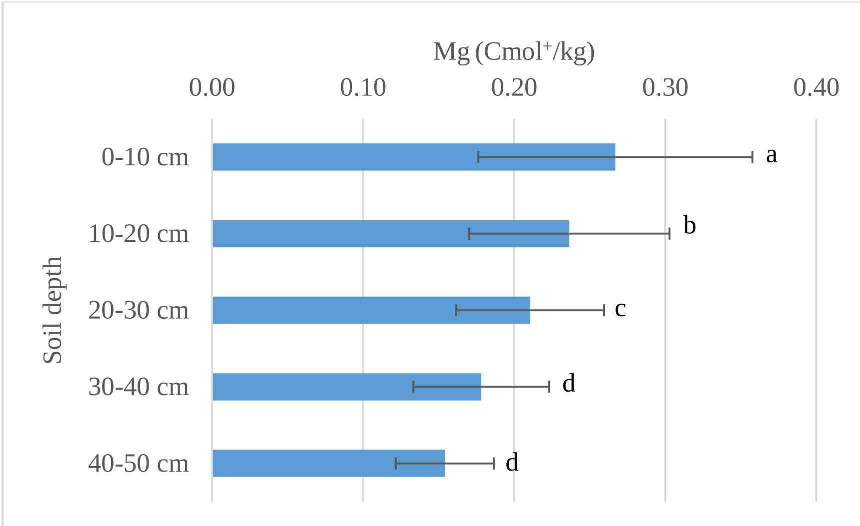


Figure 22. Soil Mg for the five soil depths. Each mean includes values from all tree species and crown positions, with 36 samples at each soil depth. The horizontal bars show standard deviations and different letters show significant differences ($p<0.05$).

### 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, ***$p<0.0001$).

| **Source** | **df** | **pH** | **OC** | **$NH_4$** | **P** | **Na** | **K** | **Ca** | **Mg** |
|---|---|---|---|---|---|---|---|---|---|
| Model | 7 | ns | ns | ns | 5.93*** | ns | ns | ns | ns |
| Distance | 7 | ns | ns | ns | 3.70*** | ns | ns | ns | ns |

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).

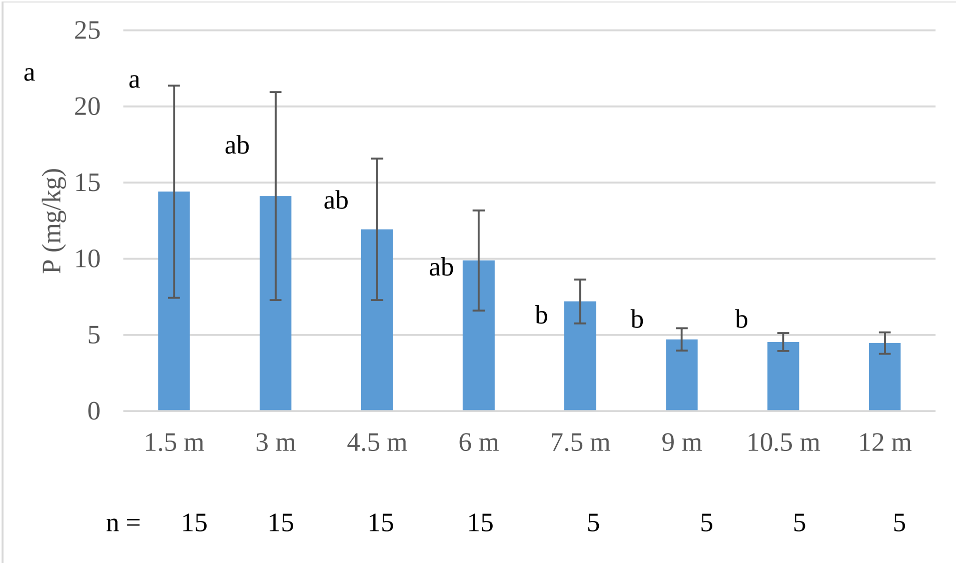


Figure 23. Soil P under *A. albida* for distance from tree trunk (n = number of soil samples). Vertical bars show standard deviation of means and different letters show significant differences between distances.

### 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).

| **Source** | **df** | **pH** | **OC** | **$NH_4$** | **P** | **Na** | **K** | **Ca** | **Mg** |
|---|---|---|---|---|---|---|---|---|---|
| Model | 1 | 45.66*** | ns | ns | 11.91** | ns | ns | ns | ns |
| Ages | 1 | 41.89*** | ns | ns | 11.17** | ns | ns | ns | ns |

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).

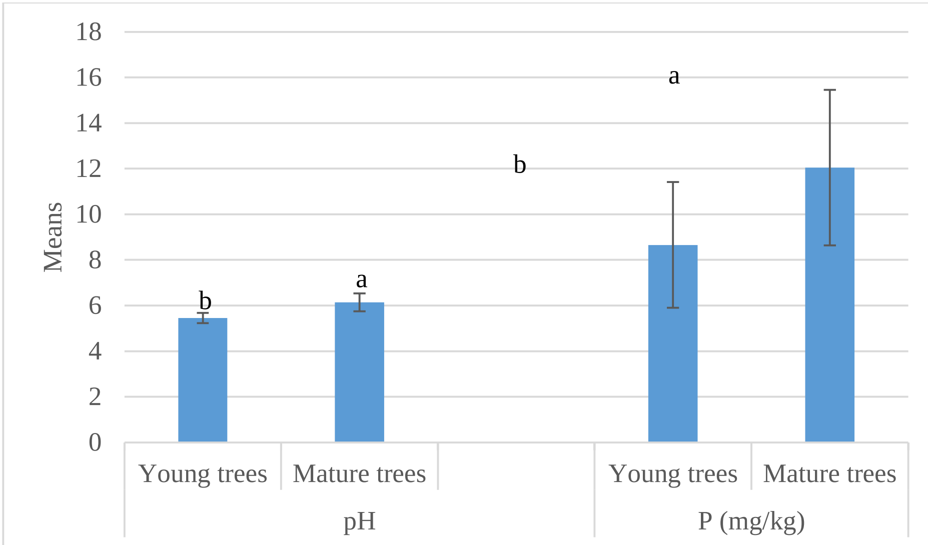


Figure 24. Soil pH and soil P for *P. reticulatum* young and mature tree (number of samples = 20 for young trees and 20 for mature trees). Vertical bars show standard deviations and different letters show differences between tree ages.

## 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 *Sequoiadendron 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.

**ACKNOWLEDGEMENTS**

I would like to thank the Director of the UNU-LRT Program and all staff for this opportunity to be one of the fellows in 2016 from Niger. I thank Berglind Orradóttir, deputy of this program to make this project a success with her laudable remarks.

I want to acknowledge the project CerLiveTrees (CLT) for funding the field work and the ICRISAT Sahelian Center, especially Dr. Fatondji, for seeing to funding the soil analysis.

My thanks go to Boukary Abdou (INRAN, Niger) for technical support and the farmers of Korto (Dantchandou) for making their fields available. Further thanks to all my supervisors ,especially Úlfur Óskarsson who went through the manuscript with valuable remarks, Dr. Abasse Toudjani (INRAN, Niger), Dr. Pierre Akponikpe (University of Parakou, Benin), and Pr. Agbossou Euloge (University of Abomey-Calavi, Benin).

I want to thank all the lecturers of the Agricultural University of Iceland and Soil Conservation Service for sharing their knowledge and experience with us.

I would also like to thank the UNU-LRT fellows of 2016 for spending their time together and sharing their knowledge and experience.

## LITERATURE CITED

Abass T, Guero C, Rinaudo T (2009) Community mobilization for improved livelihoods through tree crop management in Niger. Geojournal **74:**377-389

Abass T, Aissatou Y, Zakari AB, Adamou AI, Adam T (2013) Effet de *Piliostigma reticulatum* sur l'infestation des parcelles de mil par les insectes floricoles et *Coniesta ignefusalis* (foreur du mil) dans la zone d'Aguie au Niger. [Effect of *Piliostigma reticulatum* on millet plots infestation by flowers insects and *Coniesta ignefusalis* in Niger] Journal of Applied Biosciences **66:**5140-5146 (In French)

Adam T, Reij C, Abdoulaye T, Larwanou M, Tappan G (2006) Impacts des investissements dans la Gestion des Resources Naturalles (GRN) au Niger : Rapport de Synthèse Niamey, Niger : Centre Régional d'Enseignement Spécialisé en Agriculture [Investment impacts in Natural Resource Management (NRM) : Synthesis Report Niamey, Niger] (In French)

Akpo LE (1993) Influence du couvert ligneux sur la structure et le fonctionnement de la strate herbacée en milieu sahélien [Influence of woody species cover on the structure and functioning of the herbaceous layer in Sahel]. TDM 93 France, Paris: ORSTOM Editions (In French)

Akponikpe PBI, Gerard B and Bielders CL (2010) Soil water and crop modeling for decision support in millet based systems in the Sahel: A challenge. African Journal of Agricultural Research **9:**1700-1713

Ajayi OC and Place F (2012) Policy support for large-scale adoption of agroforestry practices: Experience from Africa and Asia. Pp. 175-201 In: Agroforestry - The Future of Global Land Use

Augustine OI, Joseph IM (1992) The effect of trees canopy cover on soil fertility in a Nigerian savanna. Journal of Tropical Ecology **8:**329-338

Bationo A, Buerkert A (2001) Soil organic carbon management for sustainable land use in Sudano-Sahelian West Africa. Nutrient Cycling in Agroecosystems **61:**131–142

Bationo A, Christianson BC & Klaij MC (1993) The effect of crop residue and fertiliser use on pearl millet yields in Niger. Fertilizer Research **349(3):** 251–258

Bationo A, Mokwunye AU (1991) Alleviating soil fertility constraints to increased crop production in West Africa: The experience in the Sahel. Fertilizer Research **29:**95-115

Bayala J, Kalinganire A, Tchoundjeu Z, Sinclair F, Garrity D (2011) Conservation agriculture with trees in the West African Sahel – A review. ICRAF Occasional Paper No. 14. Nairobi: World Agroforestry Centre

Bayala J, Kindt R, Belem M, Kalinganire A (2011) Factors affecting the dynamics of tree diversity in agroforestry parklands of cereal and cotton farming systems in Burkina Faso. New Forest **41:**281-296

Bayala J, Sileshi GW, Coe R, Kalinganire A, Tchoundjeu Z, Sinclair F, Garrity D (2012) Cereal yield response to conservation agriculture practices in drylands of West Africa: A quantitative synthesis. Journal of Arid Environment **78:**13–25

Bayala J, Teklehaimanot Z, Ouedraogo SJ (2002) Millet production under crown pruned trees in a parkland system in Burkina Faso. Agroforestry Systems **54:**203-214

Boffa JM (1999) Agroforestry parklands in sub-Saharan Africa. FAO Conservation Guide No. 34. Food and Agriculture Organization of the United Nations, Rome, Italy

Boffa JM (2000) Les parcs agro forestiers en Afrique de l'Ouest : clés de la conservation et d'une gestion durable [Parklands in West Africa : Keys to conservation and sustainable management]. Unasylva 200, **51:**11-17 (In French)

Béchir AB (2004) Evaluation des potentialités de production de la forêt classée de Bansié (Zone sud-soudanienne du Burkina Faso) [Potential production evaluation in the classified forest of Bansié (South Sudan zone of Burkina Faso)]. Mémoire D.E.A. Université de Ouagadougou, Burkina Faso (In French)

Belsky AJ, Amundson RG, Duxbury JM, Riha SJ, Ali AR, Mwonga SM (1989) The effect of trees on their physical, chemical and biological environments in a semi-arid savanna of Kenya. Journal of Applied Ecology **26(3):**1005-1024

Bhojvaid PP and Timmer VR (1998) Soil dynamics in an age sequence of *Prosopis juliflora* planted for sodic soil restoration in India. Forest Ecology and Management **106:**181-193

Bonkoungou EG, Ayuk ET, Zoungrana I (1997) Les parcs agroforestiers des zones semi-arides d'Afrique de l'Ouest [Agroforestry parklands of semiarid areas in West Africa]. Centre International pour la Recherche en Agroforesterie ICRAF, Nairobi- Kenya (In French)

Boserup E (1970) Women's role in economic development. Earthscan, London

Brouwer J and Bouma J (1997) Soil and Crop Growth Variability in the Sahel: Highlights of Research (1990-1995) at ICRISAT Sahelian Center (Information Bulletin No. 49). ICRISAT, Patancheru, Andhra Pradesh, India.

Buerkert A, Michels K, Lamers JPA, Marschner H, Bationo A (1996) Anti-erosive, soil physical and nutritional effects of crop residues. Pp. 123-138 In: Buerkert B, Allison BE, von Oppen M (eds.) Wind Erosion in Niger: Implications and Control Measures in a Millet-Based Farming System. Kluwer Academic Publishers, Dordrecht, The Netherlands

Casenave A and Valentin C (1992) A runoff classification system based on surface features criteria in semi-arid areas of West Africa. Journal of Hydrology **130:**231-249

Cunningham PJ, Abasse T (2005) Reforesting the Sahel: Farmer Managed Natural Regeneration. Pp. 75-80 In: Kalinganire A, Niang A, Kone A (eds.) Domestication des espèces agroforestières au Sahel: situation actuelle et perspectives [Agroforestry species domestication in Sahel: current situation and outlook]. Working Paper. World Agroforestry Centre, Nairobi, Kenya (In French)

Diarra FS (2010) Evaluation des arbres et arbustes fourragers indigènes au bien-être socio-économique des paysans du terroir de Koutiala, Mali [Evaluation of native trees and shrubs fodder for healthy and socioeconomic conditions of local farmers Koutiala, Mali]. M. Sc. Dissertation in Agroforestry (In French)

Ekelund F, Ronn R, Christensen S (2001) Distribution with depth of Protozoa, bacteria and fungi in soil profiles from three Danish forest sites. Soil Biology and Biochemistry **33:**475-481

Fall ST, Friot D, Richard D, H Guerin (2002) Utilisation des ligneux fourragers dans l'alimentation des ruminants domestiques en Zone Sahélienne. [Use of tree fodder in domestic ruminants in Sahelian Zone. Senegalese Institute of Agricultural Research]. Institut Sénégalais de Recherches Agricoles (ISRA) Senegal, Dakar (In French) http://www.sist.sn/gsdl/collect/publi/index/assoc/HASHbe8c/4feda153.dir/doc.pdf (accessed on 3 June 2016)

FAO (2011) The role of women in agriculture. ESA Working Paper No 11-02 Rome, Italy. http://www.fao.org/docrep/013/am307e/am307e00.pdf (accessed on 1st September 2016)

FAO (2008) Guide to laboratory establishment for plant nutrient analysis. Fertilizer and plant nutrition, Bulletin No. 9. Rome, Italy. ftp://ftp.fao.org/agl/agll/docs/fpnb19.pdf (accessed on 24 August 2016)

Fatondji D, Martius C, Bielders CL, Vlek PLG, Bationo A, Gerard B (2006) Effect of planting technique and amendment type on pearl millet yield, nutrient uptake and water use on degraded land in Niger. Nutrient Cycling in Agroecosystems **76:**203-217

Faye MD, Weber JC, Mounkoro B, Dakouo JM (2010) Contribution of parkland trees to farmers' livelihoods: A case study from Mali. Development in Practice **20(3):**428–434

Faye MD, Weber JC, Abasse TA, Boureima M, Larwanou M, Bationo AB, Diallo BO, Sigué H, Dakouo JM, Samaké O, Sonogo Diaité D (2011) Farmers' preferences for tree functions and species in the West African Sahel. Forest, Trees and Livelihoods **20:**113-136

Gandah M, Bouma J, Brouwer J, Duivendooden VN (1998) Use of a scoring technique to assess the effect of field variability on yield of pearl millet grown on three Alfisols in Niger. Netherlands. Journal of Agricultural Science **46:**39–51

Gladwin CH (2002) Gender and Soil Fertility in Africa: Introduction. African studies quarterly **6(1-2):**1-26

Gray L and Kevane M (2008) Diminished access, diverted exclusion: Women and land tenure in Sub-Saharan Africa. University of California/Santa Clara University.

Grouzis M and Akpo LE (2006) Interactions arbre-herbe au Sahel. [Tree-grass interaction in Sahel]. Secheresse **17(1-2):**318-325 (In French)

Haglund E, Ndjeunga J, Snook L, Pasternak D (2011) Dry land tree management for improved household livelihoods: Farmer Managed Natural Regeneration in Niger. Journal of Environmental Management **92:**1696-1705

Hayashi K, Matsumoto N, Hayashi ET, Abdoulaye T, Shinjo H, Tabo Matsunaga R and Tobita S (2012) Estimation of nitrogen flow within a village-farm model in Fakara region in Niger, Sahelian zone of West Africa. Nutrient Cycling Agroecosystems **92:**289-304

Hiernaux P and Ayantunde A (2004) The Fakara: A semi-arid agro-ecosystem under stress. Report of Research Activities, Niamey, Niger, ILRI/DMP

Hiernaux P and Le Houérou HN (2006) Les parcours du Sahel [Sahel Roads]. Secheresse **17(1-2):**51-71 (In French)

ICRISAT (2009). Fertilizer micro-dosing: Boosting production in unproductive lands. http://www.icrisat.org/impacts/impact-stories/icrisat-is-fertilizer-microdosing.pdf (23 August, 2016).

IFAD (2003) Mainstreaming a gender perspective in IFAD's operations: Plan of Action 2003-2006. International Fund for Agricultural Development, Rome

Jobbagy EG, Jackson RB (2001) The distribution of soil nutrients with depth: Global patterns and the implants of plants. Biogeochemistry **53:**51-77

Jose S (2009) Agroforestry for ecosystem services and environmental benefits: An overview. Agroforestry Systems **76:**1-10

Kalinganire A, Weber JC, Uwamariya A, Kone B (2008) Improving rural livelihoods through domestication of indigenous fruit trees in parklands of the Sahel. Pp. 186–203 In: Akinnifesi FK, Leakey RRB, Ajayi OC, Sileshi G, Tchoundjeu Z, Matakala P, Kwesiga FR (eds) Indigenous fruit trees in the tropics: Domestication, utilization and commercialization. CABI International Publishing, Cambridge

Kho RM, Yacouba B, Yayé M, Katkoré, Moussa A, Iktam A, Mayaki A (2001) Separating the effect of trees on crops: The case of *Faidherbia albida* and millet in Niger. Agroforestry Systems **52:**219-238

Kiarri AS, Alhou B, Adam M, Adakal H (2014) Effect of compost amended with urea on crops yields in a strip cropping system millet/cowpea in sandy soil poor in P. Research Journal of Agricultural and Environmental Sciences 1**(2):**23-28

Kiptot E and Franzel S (2011) Gender and Agroforestry in Africa: Are Women Participating? Word Agroforestry Center ICRAF, Occasional Paper 13

Kizza NP, Aniku J, Awuma K, and Gladwin CH (2002) Gender and soil fertility in Uganda: A comparison of soil fertility indicators for women and men's agricultural plots. African Studies Quarterly **6(1-2):**27-43

Lavigne D, Toulmin P, Colin CJP and Chauveau JP (2002) Negotiating access to land in West Africa: A synthesis of findings from research on derived rights to land. Land Tenure and Resource Access in West Africa series, IIED, London

Maï Moussa KA (1996) Environnement de *Faidherbia albida*: Caractérisation, exploitation et perspective d'optimisation dans les zones soudano-sahéliennes de l'Afrique de l'Ouest du Niger [*Faidherbia albida* : Characterization, uses and outlook optimization in the Soudano-Sahelian zone of West Africa, Niger]. PhD thesis, National University of Ivory Coast (In French)

Maïga A (1987) L'arbre dans les systèmes agroforestiers traditionnels dans la province du Bazèga. Influence du karité, du néré et d'Acacia *albida* sur le sorgho et le mil [Traditionnal agroforestry trees : Influence of *Vitellaria paradoxa*, *Parkia biglobosa* and *Acacia albida* on sorghum and millet production]. Probation report, IRBET/CNRST Ouagadougou (In French)

Manu A, Pfordresher AA, Geiger SC, Wilding LP and Hoosner LR (1996) Soil parameters related to crop growth variability in western Niger, West Africa. Soil Science Society American Journal **60:**283-288

Manssour AM, Zoubeirou AM, Kadri A, Ambouta JMK, Dan Lamso N (2013) Effet de l'arbre *Acacia senegal* sur la fertilité des sols de gommerais au Niger [Effect of *Acacia senegal* on soil fertility in Niger]. International Journal of Biological and Chemical Science **7(6):**2328-2337 (In French)

Mounyratou R (2011) Dynamique intra annuelle et productivité des pâturages naturelles dans la zone soudano-sahélienne du Burkina Faso: Cas du terroir de Nobéré [Intra-annual dynamics and productivity of natural pastures in the Sudano-Sahelian zone of Burkina Faso: The case of the terroir of Nobéré]. Mémoire de fin de cycle pour l'obtention du diplôme d'ingénieur du développement rural. Option: Eaux et Forets (In French)

Moussa B, Nkonya E, Kato E, Meyer S, Johnson T, Hawkins J (2016) Economics of land degradation and improvement in Niger. Pp. 499-539 In: Economics of land degradation and improvement – A global assessment for sustainable development

Neef A (2001) Land tenure and soil conservation practices – Evidence from West Africa and Southeast Asia. Pp. 125-130 In: Stott DE, Mohtar RH and Steinhardt (2001). Sustaining the global farm. Washington DC

Nikiema A (2005) Agroforestry parkland species diversity: Uses and management in semiarid West Africa (Burkina Faso). PhD thesis, Wageningen University

Ouédraogo A., Thiombiano A, Hahn-Hadjali K, Guinko S (2005) Structure du peuplement juvénile et potentialités de régénération des ligneux dans l'Est du Burkina Faso [Structure and potential regeneration of juvenile woody population in eastern Burkina Faso]. Etude Flore Vegetation Burkina Faso **10:**17-24 (In French)

Ouédraogo O (2009) Phytosociologie, dynamique et productivité des phytocenoses du parc National d'Arly (Sud-Est du Burkina Faso) [Phytosociology, dynamics and productivity of Arly National Park phytocenoses (southeastern Burkina Faso) Doctoral thesis University of Ouagadougou]. Thèse de doctorat Université de Ouagadougou (In French)

Radersma S. 1996. Influence des arbres agroforestiers sur le sol et la strate herbacée du Sud du Sahel [Influence of agroforestry trees on soil and the herbaceous layer of Southern Sahel]. Rapports PSS Nº 26. Wageningen (In French)

Reeuwijk LP (1993) Procedures for soil analysis, fourth edition. Technical paper Nº 9. International Soil Reference and Information Centre (ISRIC)

Reij C, Tappan G, Smale M (2009) Agro-environmental transformation in the Sahel: Another kind of "green revolution". IFPRI Discussion Paper 00914. International Food Policy Research Institute, Washington, DC, USA.

ROCAFREMI (2002) Bibliographie du mil : la petite bibliothèque du Réseau Ouest Africain de Recherche sur le Mil [Millet Bibliography: the small West African Library Network for Millet Research] (In French)

Saidou A, Balogoun I, Kone B, Gnangle CP, AHO N (2012) Effet d'un système agroforestier a karite (*Vitellaria paradoxa*) sur le sol et le potentiel de production du maïs (*Zea maize*) en zone Soudanienne du Benin. International Journal of Biological and Chemical Sciences **6(5):**2066-2082 (Influence of agroforestry trees on *Vitellaria paradoxa* under the sun and the potential production of *Zea maize* in the Sudanese area of Benin] (In French)

SAS (2014) The SAS system for Windows, release 9.4. SAS Institute, Cary, North Carolina

Schlecht E, Buerkert A, Tielkes E, Bationo A (2006) A critical analysis of challenges and opportunities for soil fertility restoration in Sudano-Sahelian West Africa. Nutrient Cycling in Agroecosystems **76:**109-136

Sivakumar MVK, A Maidoukia, RD Stern (1993**)** Agroclimatology of West Africa: Niger. Information Bulletin Paper 5

Udawatta RP, Gantzer CJ, Anderson SH, Garett HE (2008a) Agroforestry and grass buffer effects on pore characteristics measured by high-resolution X-ray computed tomography. Soil Science Society American Journal **72:**295-304

Vetaas Ole R (1992) Micro-site effects of trees and shrubs in dry savannas. Journal of Vegetation Science **3:**337-344

Voortman Roelf L, Brouwer J, Peter J. Albersen (2004) Characterization of spatial soil variability and its effect on millet yield on soudano-Sahelian coversands in SW Niger. Geoderma **121:**65-82

Wezel A (2000) Scattered shrubs in pearl millet fields in semiarid Niger: Effect on millet production. Agroforestry Systems **48:**219-228

Wezel A, Rajot JL and Herbrig C (2000) Influence of shrubs on soil characteristics and their function in Sahelian agro-ecosystems in semi-arid Niger. Journal of Arid Environments **44:**383-398

World Bank (2007) Gender and economic growth in Kenya: Unleashing the power of women. World Bank, Washington DC

Word Resource Institute Working paper (2013) Improving land and water management. Installment 4 of "Creating a Sustainable Food Future" https://www.wri.org/sites/default/files/improving_land_and_water_management_0.pdf (accessed 20 April 2016)

Zinke PJ (1962) The pattern of individual forest trees on soil properties. Ecological Society of America **43(1):**130-133

Zinke PJ and Crocker LR (1962) The influence of giant sequoia on soil properties. Forest Science **8:**2-11

Zhong YS and Zhao HL (2003) Soil properties and plant species in an age sequence of *Caragana microphylla* plantations in the Horqin sandy land, north China. Ecological Engineering **20:**223-235