Roles of *Leucaena leucocephala* (Lam.) on Sandy Loam Soil pH, Organic Matter, Bulk Density, Water-Holding Capacity and Carbon Stock Under Humid Lowland Tropical Climatic Conditions

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Abstract

Leucaena (*Leucaena leucocephala* Lam.) trees planted in alley cropping or established on fallowed farms by natural means contribute significantly to soil health and productivity by influencing various soil properties. In this study, the effects of *L. leucocephala* (Lam.) on sandy loam soil pH, organic matter content, bulk density, water-holding capacity and carbon stock were investigated under humid lowland tropical climatic conditions in Papua New Guinea (PNG). Soil samples were collected from 60 cm deep piths dug out from 1 m and 2 m away from the base of the legume trees. The control soil samples were collected from adjacent grassland dominated by *Imperata cylindrica* (L.), 10 m away from the legume trees. In all the piths, soil samples were collected from the 0-20, 20-40 and 40-60 cm profiles. The results showed presence of the legume trees acidifies the soil (lowers pH), lowers surface soil organic carbon, improves the water holding capacity within the surface soils and helps improve bulk density, ideal for root growth. Comparatively there was more carbon in the surface soil of the grassland than under the legume trees. In most tropical regions, grasslands are often set a blaze for various land uses and the high carbon content is a potent source of CO_2 emission, contributing to the greenhouse gases (GHG) in the atmosphere. The low carbon stock measured under the legume trees means reduced emission of CO_2 when burnt and more benefits for the sandy loam soil. This study has implication for management of sandy loam soil using *L. leucocephala* (Lam.) under humid lowland tropical climatic soil conditions.

Keywords: *Leucaena leucocephala (Lam.)*, sandy loam soil, pH, bulk density, SOC, water-holding capacity, carbon stock

Introduction

In the humid tropics, most farm soils are allowed to fallow for a given period of time following crop production to allow the farm to revert to natural vegetation. When the farm soil has reverted, the natural vegetation established, depending on the duration of the fallow period and agro-climatic (and environmental) conditions, would range from a few dominant grass species, such as *I. cylindrica* (L.) to a combination of fast growing legume trees species, such as *L. leucocephala* (Lam.), *Gliricidia sepium* (Jacq.), *Anthonotha macrophylla* (Beauv.), *Longocarpus griffonianus* (Baill.) and other common shrubs. The grasses have poor nutrient content and therefore have limited potential to help improve the conditions of the farm soil. Some grasses may even strive on whatever nutrient that was left from the previous crop production system, leading to soil degradation and loss of fertility.

Compared to the grasses, legume trees are rich in nutrients and are able to replenish depleted soils. Legume trees such as *L. leucocephala* (Lam.) and *G. sepium* (Jacq.) have symbiotic associations with bacteria, e.g. *Clostridium* and *Astobacta*, that are capable of trapping atmospheric nitrogen which is returned to the soil when the trees die. For this reason, many legume trees are used in alley crop worldwide (Giller and Wilson, 1991). In addition, legume trees are known to improve soil organic matter, stimulate soil biological activity, improve soil structure, increase soil aeration, increase soil water-holding capacity and even make tillage operations easier (Kang *et al*., 1999; Sanginga *et al*., 1992; Doube, 1997; Warren and Zou, 2002; Imogie *et al*., 2008). Not only these, litter of legume trees contributes to improvement in cation-exchange capacity, carbon-nitrogen ratio, pH and other biological, chemical and physical soil properties (Rilling *et al*., 2007; Robinson et al., 1993; Wardle, 2002; Wardle, 2005).

The importance of legume trees on soil biological, physical and chemical properties is widely established but studies in the tropics, especially under humid lowland tropical climatic conditions such as PNG, under various land use systems is limited. We have reported in a recent study conducted under such climatic condition that fallow improves the productivity of peanut (*Arachis hypogea* L.) under continuous cropping (Aipa and Michael, 2018a). Another study following that showed that fallow increases the threshed yield of rice to 8 tonnes per hectare compared to the yield of other LUS such as manure application and crop rotation, ranging from between 8 to 8.5 tonnes per hectare (Aipa and Michael, 2018b).

We have shown from these studies that the changes in soil carbon, nitrogen, phosphorus and potassium contents were small following a period of 4 months of fallow and was dominated by three dominant grass species, *I. cylindrica* (L.), *Saccharum spontaneum* (L.) and *Rottboellia cochinchinensis* (Lour.) (Aipa and Michael, 2018a). What was not clearly established from this study is the importance of the legume trees that dominate the farm when under fallow. Therefore, this study was conducted to investigate the roles of *L. leucocephala* (Lam.) on soil pH, organic matter content, bulk density, water-holding capacity and carbon stock. Total porosity was further estimated to assess the effects of the plants on the water-holding capacity of the sandy loam soil.

Materials and Methods

Description of study site: The study site is shown in Figure 1 as per Aipa and Michael (2018a). The farm (6^{o}41‟S, 146^{o}98‟E) is located at an altitude of 65 m above sea level with a mean annual rainfall of up to 3,800 mm, which is fairly distributed throughout the year. Average daily temperature is 26.3 ^{o}C, with an average daily minimum of 22.9 ^{o}C and an average daily maximum of 29.7 ^{o} C. Annual evaporation (US Class A pan) is 2,139 mm and rainfall exceeds evaporation in each month. The climate is classified as Af (Koppen), i.e. a tropical rainy climate that exceeds 60 mm rain in the driest month.

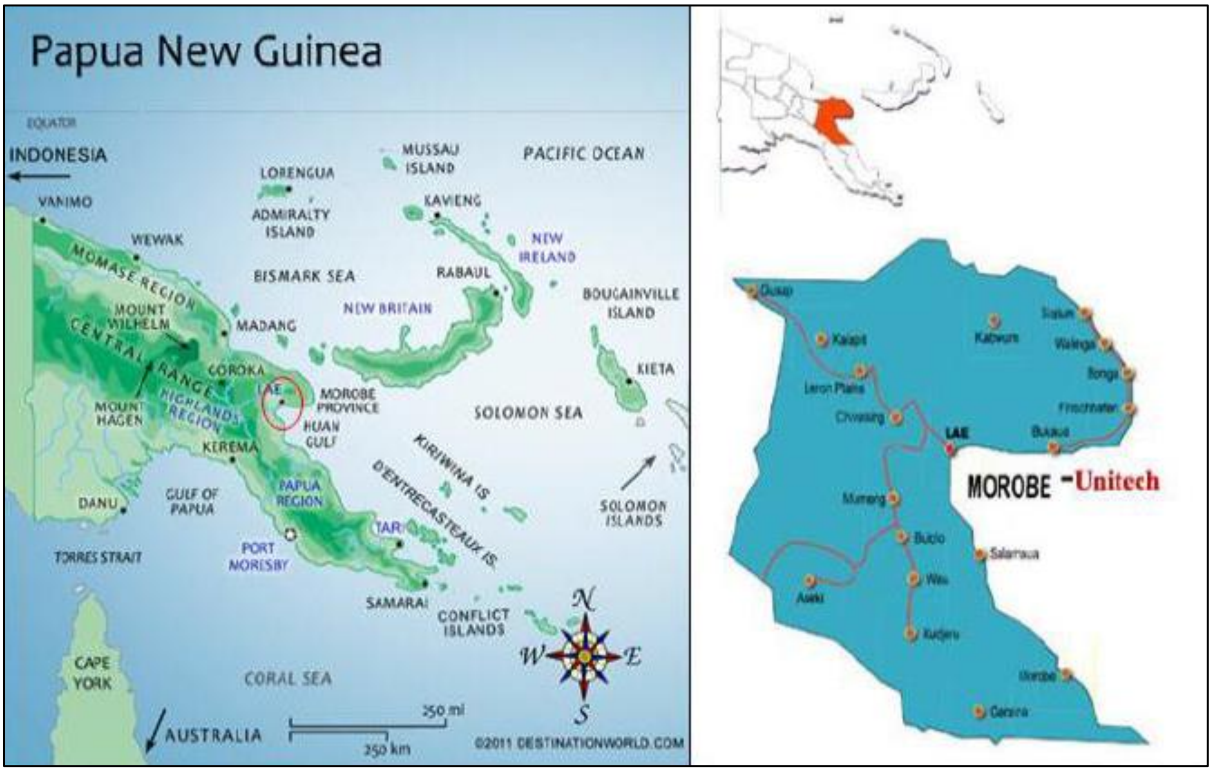

Figure 1. *Map showing the location of the study site in Lae, Morobe Province, PNG*

The soil at the experimental site is well drained, derived from alluvial deposits and is classified as a sandy, mixed isohyperthermic, Typic Tropofluents (Soil Survey Staff, 1999) or Eutric Fluvisol (World Reference Base, 2015) (Aipa and Michael, 2018a). The *L. leucocephala* (Lam.) trees and the grassland got established naturally when under fallow for nearly 10 years.

Sample collection: To collect the soil samples, a stripping method was used to dig three 60 cm deep piths. The first pith was dug 1 m away from the base of the legume trees, the second pith was dug from 2 m away from the base, and the third from a grassland. The grassland was 10 m away from the base of the legume trees and dominated by *I. cylindrica* (L.). The samples taken from the grassland were treated as the control. At each spot, e.g. in the grassland, 1 m or 2 m away, a single pith was dug. These piths were marked out into 0-20, 20-40, and 40-60 cm profiles using a 1 m ruler and triplicate samples (spadesful) were taken from each profile for analysis. The samples for bulk density calculation were taken using cores. All the samples were put in labeled air-tight plastic bags with sealed ends and placed in several buckets before taking them to the laboratory for measurements and analysis (Figure 2). A total of 180 samples, 72 samples (3 reps x 3 profiles x 4 parameters x 2 sampling locations) from under the legume trees and 36 samples (3 reps x 3 profiles x 4 parameters) from the grassland (as control) were collected.

Figure 2. *(a) Digging 60 cm piths, (b) sampling, (c) collecting samples in labeled buckets, and (d) sample photo showing the density of the legume trees of the study site*

Measurements: The soil samples collected were used to determine soil pH, soil organic carbon (SOC) content, water-holding capacity (WHC) and bulk density (BD). These were done at the University Analytical Services Laboratory, PNG University of Technology, PNG. pH was measured using the standard dilution (pH meter (1:5 soil: water w/v)) method (e.g. Michael *et al*., 2012; 2015, 2016, 2017). The soil organic carbon content (%) was analysed using the weight loss-on-ignition method (Schutle and Hopkins, 1996; Michael *et al*., 2015; 2016). A 5 g of the soil samples was placed in a crucible by weighing and heated in a muffle furnace for 12 h at 105 °C to remove moisture (W_f) and combusted again at 375 °C for 17 h (F_w), cooled for 2 h and weighed. The soil residue in the crucibles was combusted in a muffle furnace at 800 °C for 12 h, cooled for 2 h and reweighed. In studies like this, the SOC content is estimated by multiplying the carbon value by a factor of 1.72 (Aipa and Michael, 2018b). Based on this, the SOC contents (%) were calculated as:

$$\text{SOC (\%)} = [((W_f - F_w) \div W_f)100] \div 1.72 \qquad \text{Equation 1}$$

where SOC is the SOC content determined using the weight loss-on ignition method and 1.72 is the conversion factor. The conversion factor was used to convert the organic matter content to organic C, assuming there was 58% C in the organic matter. The size of the C stock in each profile was calculated as the sum of the individual C fractions (%) × g cm^{-3} × profile depth (cm) and expressed as percentage.

The water-holding capacity (WHC) was estimated as per Michael (2015) by setting soil samples at 100% water-holding capacity after soaking in water and draining through a filter overnight. These were weighed for the wet weight (Ww) and dried in an oven at 105 ^{0}C for 48 h and reweighed to obtain the oven dry weight (ODw). WHC was determined as:

$$\text{WHC}(\%) = [((\text{Ww}-\text{ODw}) \div \text{ODw})100] \qquad \text{Equation 2}$$

Bulk density (g cm^{-3}) was calculated by oven drying of the cores at 105 °C for 48 h followed by re-weighing (Aipa and Michael, 2018a). The oven dry weights were divided by the volume of the core and kept as the BD. Total porosity was determined as per Landon (1991):

$$P = \left(1 - \frac{BD}{d}\right)100 \qquad \text{Equation 3}$$

where P is total porosity (%), BD is bulk density and d is particle density equal to 2.65 g cm^{-3}.

Results and Discussion

Soil pH under various land use systems are affected by factors such as organic matter content, aeration, microbial activity and soil water status. pH in turn affects oxidation and reduction of minerals, release and mobility of minerals, and stability and availability of nutrients (Reddy and Patrick, 1977; Deshmukh, 2012). Under natural soil use conditions, more leaf litter and dead plant matter fall close to the base of plants within the surface, whereas in the deeper soil are limited to dead roots and root exudates (Michael *et al.*, 2017).

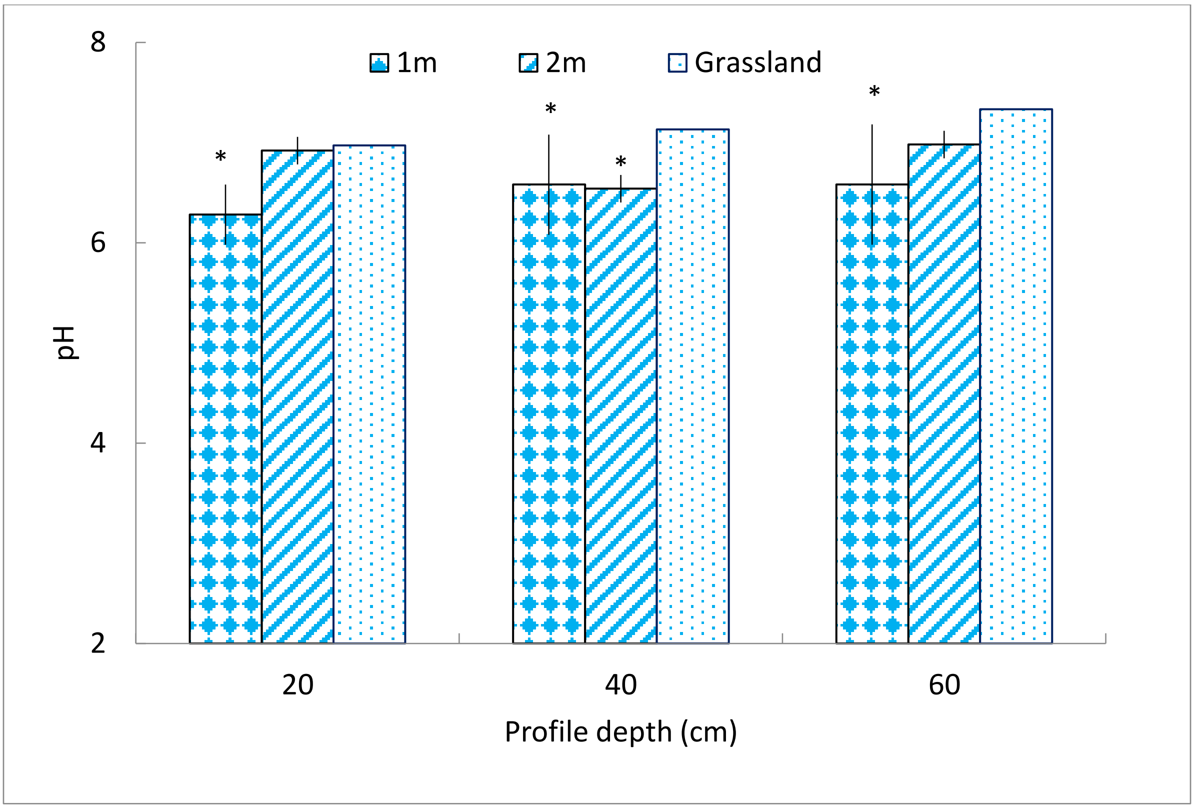

Figure 3. *Soil pH of soils 1 m and 2 m away from the base of the legume trees at different profiles. The values are mean ± s.e. of three replicates (n=3). An asterisk indicates significant difference (p<0.05) between the legume trees and the grassland at the same depth*

The changes in pH measured are shown in Figure 3. Compared to the grassland soil pH which was near 7 units throughout the profiles, presence of the legume trees acidified the soil near the base, the changes in pH ranging from between 6.3 to 6.6 units within the surface to deep. pH of the soil further from the base (2 m) within the surface (0-20 cm) was higher and similar to that of the grassland, but at the deeper profiles (20-40 cm and 40-60 cm) were lower (Figure 3). These types of variability in pH of sandy soils under different land use have been reported (Enakiev *et al*., 2018, Michael and Reid, 2018; Michael, 2015).When the pH was low in the presence of the legume trees, generally SOC content was small (Figure 4), WHC was between 20-60% (Figure 5) and BD was less than 0.4 g cm^{-3} (Figure 6). In most soils, decomposition of plant matter and release of anions and organic nitrogen lead to an increase in pH as microbes act on the resources (Michael *et al*., 2016). The opposite happens when nitrification takes place, resulting in acidification reaction and low pH. We have shown that organic matter addition in strong acidic soil (pH<4) raises pH to well above circumneutral level (e.g. Michael *et al.*, 2015, 2016, 2017). In general, presence of the legume trees acidified the soil, either near the base within the surface or 2 m away at deeper soils. Olujobi (2016) reported a pH of 7.1 within the 15-30 cm surface of a sandy loam soil with *L. leucocephala* (Lam.), compared to the pH of 6.6 units observed within the 20-40 cm (Figure 3). The small decrease in pH by 0.5 unit observed in the current study resulted from leaching of cations and nitrification of the organic nitrogen from the decomposition of plant litter. In other studies, legume trees were generally seen to increase surface soil pH by increasing Ca^{2+} level and reduction of exchangeable H^{+} (Drechsel *et al*., 1991; Madukwe *et al*., 2008).

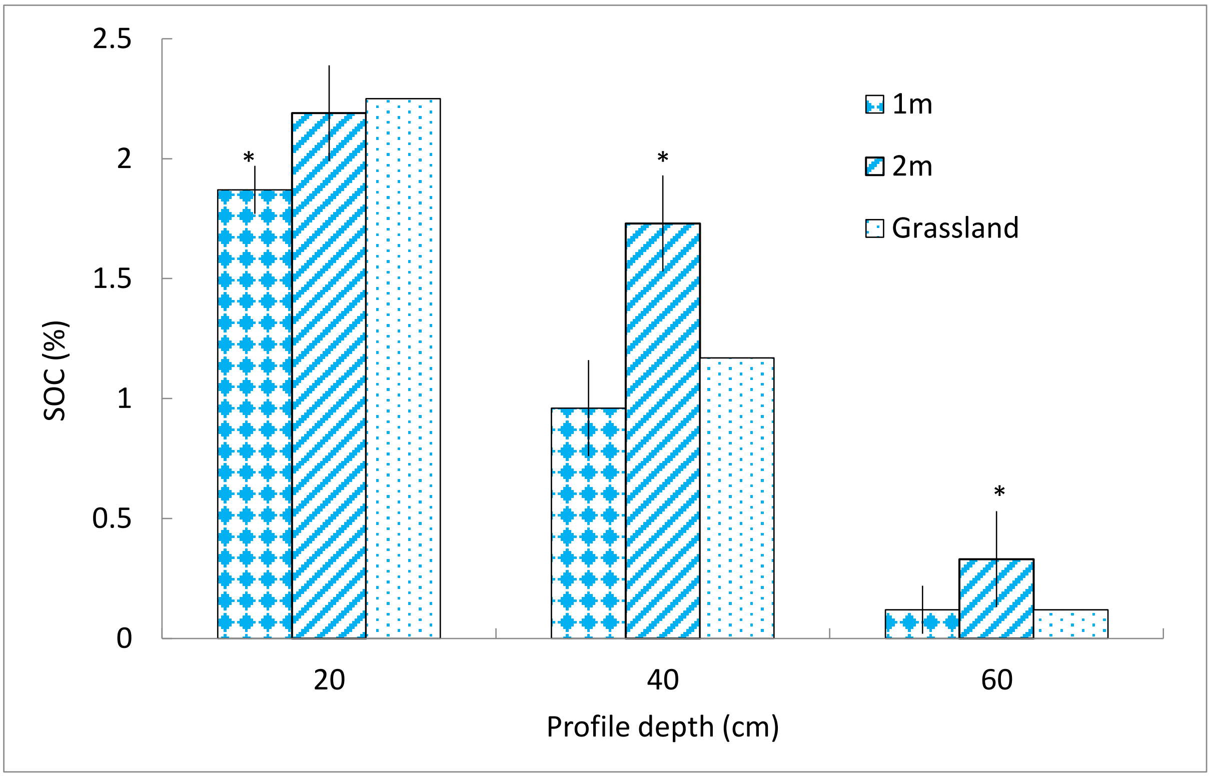

Figure 4. *Soil organic carbon content of soils 1 m and 2 m away from the base of the legume trees at different profiles. The values are mean ± s.e. of three replicates (n=3). An asterisk indicates significant difference (p<0.05) between the legume trees and the grassland at the same depth*

The SOC contents and the changes in C stock are shown Figure 4 and Table 1, respectively. In all soil types, SOC is important for various biological, physical and chemical processes that are needed for soil health and productivity (Bais *et al*., 2006; Bell *et al*., 2005; Bossuyt *et al*., 2004; Michael, 2018). For example, SOC regulates pH, redox, cation-exchange capacity, enhances water-holding capacity (Kang *et al*., 1990) and aerates soils (Imogie *et al*., 2008). The SOC contents near the legume trees (1 m) and 2 m away within the surface soils (0-20 cm) were small, ranging from between 1.9-2.2%. Generally, high SOC content resulted in small porosity, indicating organic matter availability reduced pore spaces. For example, when the grassland SOC content was 150%, the porosity was reduced by nearly 43%.

In the deep soils (20-40 cm and 40-60 cm), the SOC contents were much smaller and nearly the same except that a small increase was found at the 40 cm profile in the soil 2 m away from the base of the legume trees (Figure 4). This probably is due to high turnover of organic matter from the legume trees as well as the grass that got established further from the base of the legume trees as a result of low canopy. These results agree with Olujobi (2016) who reported SOC contents of 1.7% within a 15-30 cm profile under *L. leucocephala* (Lam.). A similar observation was made in this study. The SOC contents were decreasing from the surface to the deep soils, more so in the grassland. For instance, the SOC content decreased from 2.3% at the surface to 0.1% at deep. When the organic matter in the SOC was converted to C using Equation 1, a significant decrease was observed under the two *LUS* (Table 1).

Table 1.*The C stock (%) was decreasing from the surface to deep soils*

	Sampling	**Profile depth** (cm)		
LUS	**location**	0-20	20-40	40-60
Legume trees	1 m	8.0±0.2*	8.0±0.3*	1.8±0.2*
	2 m	9.0±0.3*	14.0±0.2*	5.0±0.2*
Grassland	Single spot	152.0±0.3	34.0±0.2	7.0±0.3

An asterisk indicates significant difference ($p<0.05$) between the legume trees and the grassland at the same depth.

The effects of C stock on pH, WHC and BD are shown Table 2. The general trend shown is that as C stock was decreasing, soil pH was decreasing, WHC was above 50% and BD was <0.5 g cm^{-3}. A similar loss in SOC content by 10.1% (1.8/17.8 from Table 1) was observed in the soil closer to the legume trees. For example, 1.9% SOC content within the surface (0-20 cm) decreased to 0.12% at deep soil (40-60 cm) (Figure 4), a loss of C stock by 4.1% (0.12/2.95x100). These results demonstrated that the C stock was high within the surface, probably due to high turnover of organic matter. In deep soils, the C stock decreased (Table 2), indicating the sources of carbon addition there were limited. These results agree with the common knowledge that most of the organic matter from live plants end up within the surface soils (Michael, 2017). Sandy soils have poor water retention and require significant amount of organic matter to be present to hold water. The results of this study showed that *L. leucocephaha* (Lam.) has the potential to improve surface SOC content and the C stock (Table 1) sufficient (>55%) reduce porosity and hold water to support growth of plants.

The legume tree is perennial; therefore turnover of organic matter at deeper soils is expected to be small as more roots are alive then dead to provide sufficient organic matter, whereas the grass species is expected to turnover organic matter (e.g. dead roots) more quickly being an annual, building up the SOC content and the C stock. In soils with smaller plants, organic matter accumulation from senescent plant material is small but much quicker, resulting in much higher SOC content, making them an important source of energy for the sandy soil. In the tropics, most of the grasslands are subjected to frequent fires, making the high C stock in the grassland a potent source of CO_2 for greenhouse gas (GHG) emission. This study showed that having legume trees in grasslands would offset this GHG emission problem by the lowering the C stock in soils (Table 2).

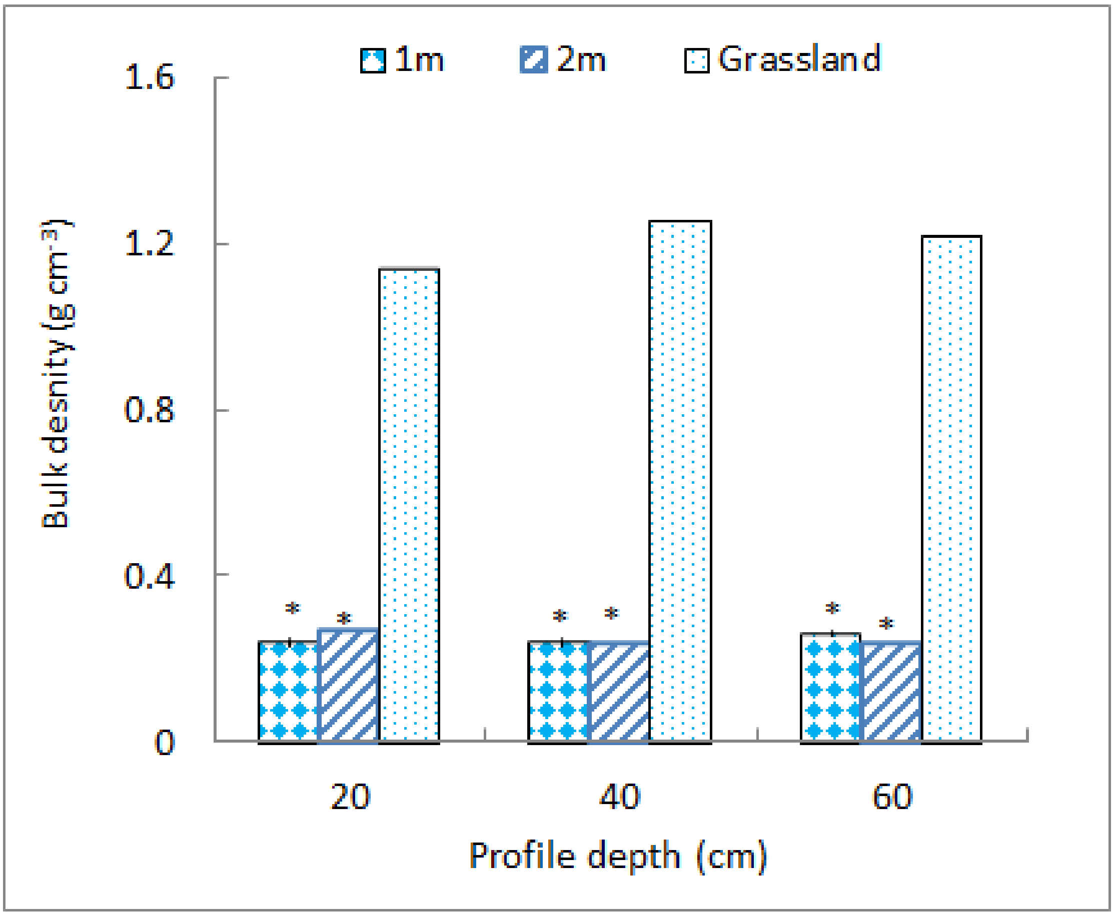

Figure 5. *Bulk density of soils 1 m and 2 m away from the base of the legume trees at different profiles. The values are mean ± s.e. of three replicates (n=3). An asterisk indicates significant difference ($p<0.05$) between the legume trees and the grassland at the same depth*

Bulk density is a measure of soil structure and in most soils increases with depth. The BD measured in the grassland was near 1.2 g cm^{-3} (Figure 5), consistent with 1.4 g cm^{-3} of Aipa and Michael (2018a). In the presence of the legume trees, BD decreased to below 0.5 g cm^{-3}, near and further from the base of the legume trees. In the same sandy soil, when rice was continuously cultivated, rotated with maize or fallowed for 4 months, BD remained nearly unchanged (Aipa and Michael, 2018a), the BD being same as that of the grassland soil of this study. These results indicate that BD is strongly affected by the changes in pH, SOC content and the WHC. For example, BD was small when WHC (Figure 6) or pH (Figure 3) was small. The general trend in BD observed ranged from less than 0.5 g cm^{-3} in the presence of the legume trees to 1.4 g cm^{-3} in the grassland, showing the BD was ideal for optimum root growth (Eche *et al*., 2013). A decrease in C resulted in increase in BD (Table 2). As expected, total porosity was high in the surface soil and smaller at the deep soil (Table 2), supporting the common knowledge root sizes is bigger within the surface soils and smaller at deep soil as roots branch out. The porosity of the grassland was fairly constant, ranging from between 57% within the surface to 54% at the deep soils. This means the high SOC content in the grassland was sufficient to reduce the pore spaces in the sandy loam soil, and the small roots and the shallow rooting systems of the grass plant were not enough to increase porosity.

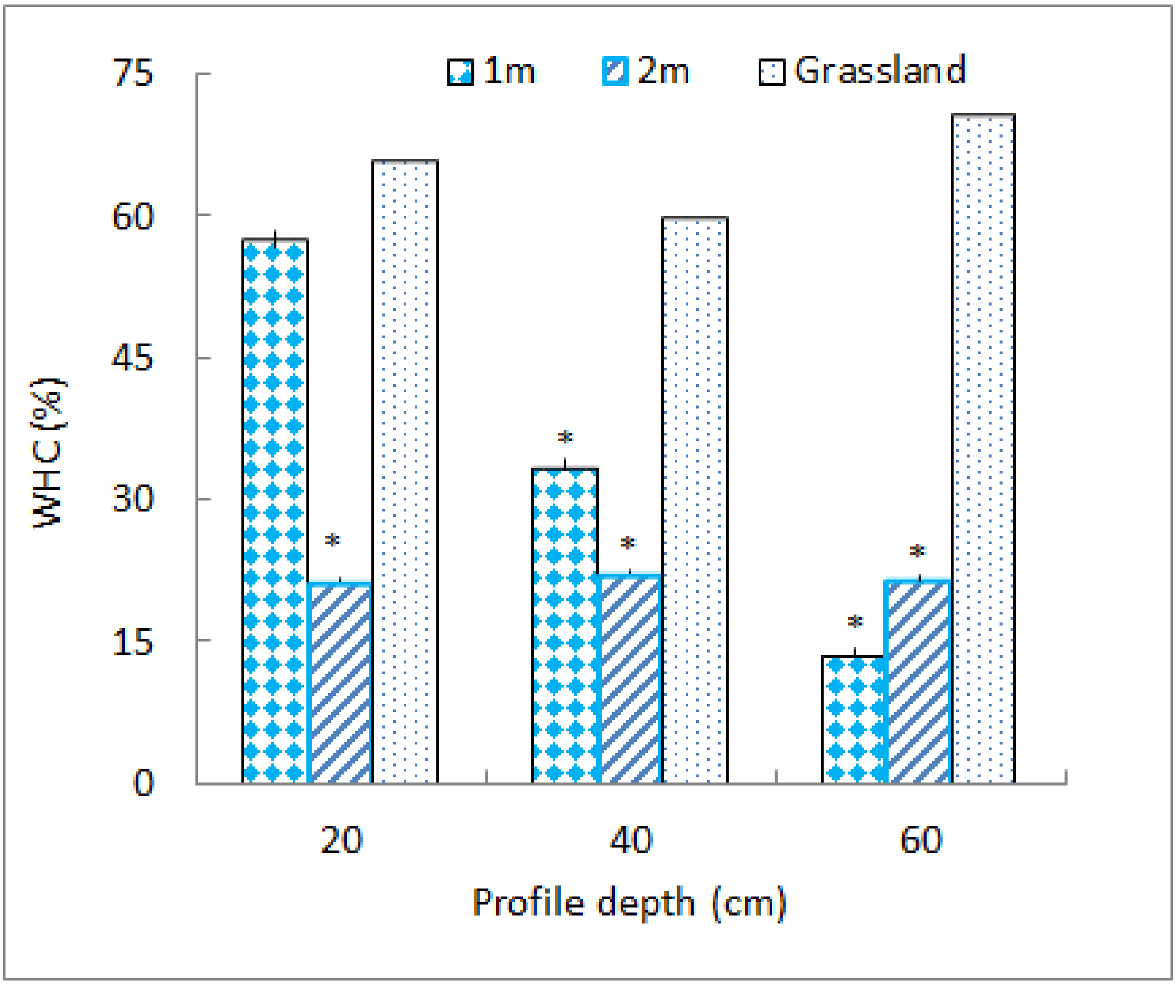

Figure 6. *Water-holding capacity of soils 1 m and 2 m away from the base of the legume trees at different profiles. The values are mean ± s.e. of three replicates (n=3). An asterisk indicates significant difference ($p<0.05$) between the legume trees and the grassland at the same depth*

The variability in WHC measured is shown in Figure 6. In the grassland, WHC was fairly constant throughout, ranging from between 60-75% (Figure 6). Compared to that, WHC was near 60% within the 0-20 cm soils 1 m away from the base of the legume trees. This decreased to near 30% within the 20-40 cm soils and further decreased to below 15% at 60 cm. These results did not show a clear relationship between BD and pH but as SOC content was high, WHC is high and as it decreases, WHC decreases. For example, within the 0-20 cm soil, WHC was the highest (Figure 6), corresponding to the highest SOC content of 1.9% measured within the same profile (Figure 4).

The relationship that exists between WHC and C stock near the legume trees (1 m) is shown in Table 2. As the SOC content decreased to 0.1% at the 40-60 cm profile, the WHC decreased to near 15%, a strong indication that SOC content affects the WHC (Figure 6). This variability was found only in the soils closer to the legume trees. Further from the base (2 m), WHC was fairly constant around 22% in all the profiles (Figure 6). These types of variability are common under natural soil conditions because the turnover of organic matter is entirely variable, dependent on the plant types, age, litter type and growth conditions etc. We observed turnover organic matter decreasing and lesser litter shed by several deep rooted plants in acid sulfate soils (Michael *et al*., 2017).

When the variability in WHC was compared to the C stock, there was a direct relationship between the changes in WHC and the C stock (Table 2). The highest C stock of 8% corresponded to the highest WHC of more than 50%, compared to the proportionate change observed at depths. Comparatively, WHC was small in soils pH and BD were small, and was high when these were high (Table 2). For example, when the WHC was 56%, pH was near 6 units and BD was below 0.5 g cm^{-3}.

Table 2. *Effects of carbon stock on soil pH, bulk density and water-holding capacity*

Depth (cm)	C stock (%)	pH	WHC (%)	BD (g cm^{-3})	Porosity (%)
0-20	8.0±0.2	6.3±0.3	56±0.4	0.2±0.4	92.45±0.1
20-40	8.0±0.3	6.6±0.5	34±0.5	0.2±0.1	92.45±0.1
40-60	1.8±0.2	6.6±0.6	14±0.2	0.3±0.4	88.68±0.3

In sandy soils, water retention is poor and a significant proportion of organic matter is needed to retain soil moisture for root growth. This study showed presence of *L. leucocephaha* (Lam.) lowers WHC of sandy loam soils to well below 60%, whereas presence of annual grass *I. cylindrica* (L.) helps keep the WHC above 60%. This variability resulted from the variability in SOC content measured shown in Figure 4. The possible reason for the decrease in WHC at deep soils resulted from increase in porosity caused by the bigger roots and the deep rooting systems of the legume trees (Table 2), compared to the impacts of the smaller roots and shallow rooting systems of the grass plant whose effect on porosity was near 50%. The high C stock in the surface soil in the grassland (Table 1) also resulted from the small and shallow rooting systems of the grass whose plant matter mostly accumulates within the surface soil than at the deeper soils (Table 2).

Conclusion

Under different land use and management systems in the tropics, most fallowed farmlands are dominated by perennial legume trees species like *L. leucocephala* (Lam.) and annual grass species such as *I. cylindria* (L.). The importance of these types of plants on soil properties are often not reported from this region. This study showed presence of *L. leucocephala* (Lam.) acidified the soil, increased surface SOC content, improved the BD ideal for optimum growth of roots, and retained surface soil moisture by reducing porosity. The surface soil C stock was sufficient to support normal plant growth although was small compared to that of the grassland. During the drier seasons, fallowed farmlands with dominant annual grass are often set on fire by farmers to prepare the land for the next use. The high C stock found in the grassland under such a circumstance is a potential source of CO_2, contributing to the GHG emission. The results showed purposive establishment of *L. leucocephala* (Lam.) in farmlands under general soil use and management system would help improve conditions of sandy loam soil, reduces C stock to level sufficient to support good soil health and productivity and help reduce CO_2 emission during fire events. In addition, use of *L. leucocephala* (Lam.) in fallow would provide nitrogen, important for sustainable use of the sandy loam soil.

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