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SOIL PHYSICAL QUALITY INDICES AND GROWTH OF JUVELINE TUNG BIOENERGY OIL TREE AS AFFECTED BY COVER CROP INTERCROPPING AND ADDITIONAL POULTRY MANURE

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ABSTRACT

This study aimed to evaluate the impacts of cover crop intercropping and poultry manure on soil physical quality indices and tung growth in a tung-based agroforestry system. Intercropped cover crops increased soil organic carbon, reduced bulk density and relative field capacity, increased available water, saturated hydraulic conductivity, air capacity, ratio air capacity/total porosity, and total nitrogen of the surface layer of the tung-based agroforestry system at the end of the two growing seasons. The soil quality index of the surface layer changed from low to average in tung plots with cover crops and followed the order: Tung+Crambe/Sunflower/Soybean ≈ Tung+Oat/Vetch/Peanut > sole tung. Poultry manure enhanced further the physical quality status of the tung field. The unprotected tung soil (sole tung) of the tung-based agroforestry system is degrading, thus conservation strategies including those evaluated in this study are advocated for securing the growing environment of juveline tree crops as well as achieving their production potentials.

Keywords: Biodiesel tree crops, cover crop intercropping, organic manure, agroforestry system, soil physical quality

INTRODUCTION

The availability of feedstocks for biodiesel production is one of the most significant requirements for biodiesel production. Globally, more than three hundred oil crops have been identified as potential feedstocks for biodiesel, classified as edible and non-edible oils (ATABANI et al., 2013).

There have been reports of biodiesel production from edible and non-edible feed stocks including jatropha (*Jatropha curcas*) (CHEAH et al., 2016; OKULLO et al., 2012), rapeseed (KNOTHE et al., 1997), castor seed (CHEAH et al., 2016; NDAMA et al., 2011; ISMAIL et al., 2014), tung tree (*Aleurites* spp.) (CHEN et al., 2010; SHANG et al., 2010; SHARMA et al., 2011; ZORNITTA et al., 2017), sunflower seed (KNOTHE et al., 1997; REFAAT et al., 2008), rubber seed (KANT et al., 2011; RAMADHAS et al., 2004), jojoba (*Simmondsia chinensis*) (BORUGADDA & GOUD, 2012), oil palm (CHEAH et al., 2016; SAKDASRI et al., 2017), neem (*Azadirachta indica*) (ANYA et al., 2012; ARANSIOLA et al., 2012), sugarcane (*Saccharum oficinarum*) (BRIENZO et al., 2015; ISMAIL & ALI, 2015).

The main limitation of biodiesel from edible oil feedstocks today has been linked with the debate on “food or fuel”, at which the rising prices in food items are somehow associated to the increasing emphasis on energy crop cultivation over food crops. Hence, the shift towards feedstocks that are non-edible which are receiving attention in many countries, considered very economical compared with edible feedstocks (DEMIRBAS et al., 2016) and strive well in marginal lands considered not suitable for food crop production.

Tung (*Aleutites* spp.), a family of Euphorbiacea, is one of the non-edible oils reported to originate from China where it has been grown for its oil used to make vanishes, paints, and resin (DUKE, 1983). With the importance of tung oil more recognized, it has been introduced and is now cultivated in many countries beyond China, such as in Brazil, Argentina, Paraguay, Africa, India and the United States (AVILA et al., 2010; SHARMA et al., 2011). In Brazil, tung is cultivated in the Southern region (Parana and Rio Grande do Sul States) where the condition of at least 350 chilling hours of temperature below 7.2 ^{o}C for bud initiation (EICHOLZ, 2016). In Rio Grande do Sul State, tung was reported to have been in existence for over 50 years but it was abandoned as a result of poor market and patronage (ZORNITTA, 2014), However, with the emergence of the National Biodiesel Production and Use Program, the bioenergy market is consolidating in Brazil, indicating the need to expand production scale and alternatives for diversifying the oilseed matrix and today about 19 munipalities in the Serra Gaucha are cultivating tung on commercial scale (AVILA, 2010). Duke (1983) reported that tung seeds contains about 30 - 40% oil but this proportion has increased with improvement in technology and extraction methods. Kautz et al. (2008) extracted about 41% oil from tung seeds and were able to transform 87% of this oil into biodiesel, Avila et al. (2010) obtained about 47% oil from tung seeds, and more recently, Zornitta (2014) extracted about 50% oil from tung seeds, showing high oil level and the potential for biodiesel production.

Tung has been established in spacings ranging from 2 m x 2 m to 10 m x10 m, depending on cultural practices and usage (AVILA et al., 2010). In tung plantations with spacings from 5 m x 5 m, gaps between plant stands can be utilized to cultivate other early maturing energy crops to complement the biodiesel supply chain and maximize land use. Apart from the opportunity of exploring the biological efficiency of the land, the soil surface is without or with vegetation cover at the intial stage of crop development, giving room for soil structural degradation. Substantial nutrient and soil losses from bare soils in runoff and sediments have been quantified and reported (BASHAGALUKE et al., 2018; BERTOL et al., 2017; REICHERT et al., 2019).

Conservation agriculture programs such as organic amendment, intercropping, no-tillage, agroforestry, cover crops, etc have been advocated and successful implemented in different climate with a view to protecting the soil surface, and securing the soil for increased productivity and functionality as well as ensuring a sustainable environment (ANDRADE et al., 2009; AWE et al., 2015a, AWE et al., 2015b; AWE et al., 2020; BORJA REIS et al., 2017; BUKOVSKY-REYES et al., 2019; ENSINOS et al., 2016; NASCENTE & STONE, 2018; REICHERT et al., 2022; WEERASEKARA et al., 2017; WEILER et al., 2019). However, for the soil to be productive, functional, and contribute to ecosystem services, its quality is of paramount important which must be accorded priority at all times.

Soil quality is central to agricultural sustainability Doran and Zeiss (2000), and the concept has been used as an indicator to assess the effect of both natural and anthrogenic factors such as climatic conditions, lithology, land use, soil and crop management (CHEN et al., 2006; EL-LADAN et al., 2015; MANDAL et al., 2013; TESFAHUNEGN, 2014) on soil functions. For example adequate knowledge of the effect of various soil and crop management practices on soil health is required for sustainable crop production systems. Thus, the need to investigate soil quality has received considerable research attention as the soil remains a major actor not only for food security but also in maintaining environmental quality (DORAN et al., 1994; FAGERIA, 2007; VARGAS et al., 2016). Researchers have sought to obtain a set of soil quality (SQ) indicators to evaluate the land with respect to degradation or improvement, monitor changes in soil properties to evaluate the efficiency of management options, investigate how sustainable the soil resource base is, as well as how the environment faired over a given period (DE SOUZA et al., 2019; STEFANOSKI et al., 2016; TESFAHUNEGN, 2014).

Because of the complexity of the various soil quality indicators, it has been difficult to use one indicator or a group of indicators to qualify the overall soil quality status. Therefore, an overall index that combines all the indicators, otherwise known as the soil quality index (SQI), has been developed to assess agroecosystem sustainability (ANDREWS et al., 2002). This index has been adopted globally and it has been much easier to classify the overall quality status of the soil, with recommendations made for sustainable management practices. Several studies have found the soils to be either high, moderate or low in quality (AZIZ et al., 2011; CHERUBIN et al., 2017; CHERUBIN et al., 2018; DEMIR et al., 2019; GELAW et al., 2015; JOKELA et al., 2009; SEKER et al., 2017; TESFAHUNEGN, 2014; YAO et al., 2013). Despite this quatum of studies, little is known about the quality status of the soil environment where the tung crops grows.

We hypothesized that (i) short-term cover crops intercropping and addition of poultry manure significantly increased soil organic carbon and improved soil physical quality indices of the tung-based agroforestry system, and (ii) increased carbon inputs from cover crops and poultry manure significantly influenced tung growth. The objectives of this study were to evaluate the effect of intercropped cover crops and additional poultry manure on (i) soil physical quality indices of a juvenile tung-based agroforestry system and (ii) tung growth in a two-year study in southern Brazil.

MATERIALS AND METHODS

The juveline tung field is located at the Research Stattion, Soils Department, Federal University of Santa Maria, Santa Maria, Rio Grande do Sul State, Brazil. The station is located on latitude 29° 42' S, longitude 53° 49' W, and 95 m above the sea level. The climate is classified as "Cfa", humid subtropical by Köppen (MORENO, 1961). The mean daily temperature during the summer is above 22°C while the winter period have temperature ranging from -3°C to 28°C. The total annual rainfall is about 1650 mm. According to Soil Survey Staff (2010) classification, the soil type of the study area is *Dystrophic Paleudalf*, with the surface layer of sandy loam texture. The pH of the 0 - 10, 10 - 20, and 20 - 40 cm soil layers ranged between 5.8 and 6.0. Avalialbe P had values between 3.0 and 29.0 mg dm^{-3}, and excheangeable K ranged 3.6 and 10.8 cmolc dm^{-3}. Cation exchange capacity ranged from 9.3 to 10.4 cmolc dm^{-3}, base saturation was relatively high, ranging between 69.5 and 72.2%, and excheangeable aluminum was not detected, while the soil physicochemical properties decreased with soil depth.

This experiment was laid out in randomized complete block design (RCBD), with a special split plot arrangement and in four replications. The trials were made during two contrasting winter and summer periods of two growing seasons. During the winter period, the treatments consisted of tung + crambe (Tung+Cr), tung + oats + vetch (Tung+Ot/V), and control (sole tung), while for the summer period, the treatments were tung + sunflower/soybean rotation (Tung+Su/So), tung + peanut (Tung+PN), and control (sole tung). The Tung+Cr and Tung+Su/So plots were divided into three, one subplot of each treatment receiving poultry manure, the second subplot received NPK fertilizer while the third suplot retained the main treatment.

The oats+vetch mixture was intercropped at the rate of 60% oats and 40% vetch. The sunflower was intercropped during the summer of the first year (2012/2013), whereas soybean was intercropped during the summer of the second year (2013/2014). The summary of the treatments is presented (Table 1).

The tung was established in October of 2011 when seedlings were transplanted at a spacing of 10 m x 10 m, while the agroforestry system with cover crops started in May 2012. The winter season commenced in May and ended in October of the same year, whilst the summer season started in November and ended in April of the following year. There were 16 plots in all and each plot measures 50 m^2. Two tung seedlings were transplanted at the middle of each plot with inter- and intrarow spacing of 5 m x 10 m per plot. On both side of the tung stands, a small gap, about 0.40 m from tung centre line, was marked while the portion remaining on either side was planted to the cover crops in form of strips (Figure 1).

Sowing of the cover crops was done manually without soil disturbance between the tung plant rows. Oats+vetch seeds were broadcast and incorporated into the soil. In crambe (cultivar FMS Brilliant), the spacing used was 0.40 m x 0.075 m, giving a plant density of about 300,000 plants ha^{-1}. Hybrid sunflower (cultivar Dow AgroScience M734) was planted one plant per stand, spaced 0.45 m x 0.75 m, giving plant density of approximately 30,000 plants ha^{-1}. Peanut, cultivar Tatu, which spreads on the soil surface, was planted at plant spacing of 0.45 m x 0.20 m and one plant per stand, giving plant density of about 110,000 plants ha^{-1}. Soybean (cultivar BRS 154) was sown two plants per stand and spaced 0.40 m x 0.20 m, giving plant population of 125,000 plants ha^{-1}. Before subsequent planting, plant residues of each crop, ranging between 3.2 and 6.0 Mg/ha, was evenly spread on the soil surface of the respective plot.

Table 1. Scheme of the intercropped cover crop, poultry manure and NPK fertilization in the tung-based agroforestry system.

	Treatments	
Growing season	**Winter**	**Summer**
2012/2013	Sole tung	Sole tung
	Tung+Cr	Tung+Su
	Tung+Ot/V	Tung+PN
	Tung+Cr+PM	Tung+Su+PM
	Tung+Cr+NPK	Tung+Su+NPK
2013/2014	Sole tung	Sole tung
	Tung+Cr	Tung+So
	Tung+Ot/V	Tung+PN
	Tung+Cr+PM	Tung+So+PM
	Tung+Cr+NPK	Tung+So+NPK

Cr: crambe; Oat: black oats; V: vetch; Su: sunflower; PN: peanut; So: soybean; PM: poultry manure; NPK: fertilizer at equal amount of nitrogen, potassium and phosphorus

The quantities of NPK applied are 15 kg/ha of N, 30 kg/ha of P_2O_5, and 25 kg/ha of K_2O at sowing time, respectively as urea, triple superphosphate (SSP) and potassium chloride (KCl).

Additional 45 kg/ha of urea was also applied at 56 and 33 days after sowing (DAS) in the crambe plots respectively in 2012 and 2013/2014, and after 63 DAS in sunflower and soybean plots in 2012/2013 and 2013/2014. For the treatment that received organic fertilizer, poultry droppings (PM) was used. The PM was obtained from a Broiler House stocked with five birds/m^2. The dosage of the manure was defined based on the recommendation of the Committee of Soil Chemistry and Fertility (CQFS - RS/SC, 2004) organic fertilization, which stipulates that 50% of the total N in any organic amendment must be available to the crop. The PM was applied in as a single dose to the soil surface before sowing.

Figure 1. Tung experimental field showing a) the bare soil of the tung field being prepared for first intercropping, b) control plot, c) crambe intercrop (in winter), d) oats/vetch intercrop (in winter), e) sunflower intercrop (in summer), and f) peanut intercrop (in summer).

Shortly before imposing the treatments in 2012 and end of the 2012/2013 and 2013/2014 growing seasons (end of summer in April), disturbed and undisturbed soil samples were collected using metallic cylinders, about 100 cm^3 capacity, in the middle of soil layers of 0 - 10, 10 - 20 and 20 - 40 cm soil layers, for the determination of soil properties of particle size by pipette method (EMBRAPA, 2011); bulk density by core method (Blake and Hartge, 1986); total porosity (Pt), saturation water content (θ_s); macroporosity (Ma) -6 kPa, field capacity (FC) at -10 kPa in sand box, permanent wilting (PWP) at -1500 kPa in WP4 dew point potentiometer (GUBIANI et al., 2009; GUBIANI et al., 2012; KLUTE 1986; REINERT & REICHERT, 2006;); saturated hydraulic conductivity (Ksat) using constant-head permeameter (KLUTE & DIRKSEN, 1986), soil organic carbon (OC) and total nitrogen (TN) by dry combustion (TEDESCO et al., 1995). The ratio carbon:nitrogen and carbon pool were computed from the soil organic carbon and total nitrogen contents.

Available water (AW) was computed as water content at FC minus PWP (TOLK, 2003). Air capacity (AC) was obtained as saturation water content, θ_s minus FC (REYNOLDS et al., 2015). Relative field capacity (RFC) was computed following Reynolds et al. (2015) as:

$$RFC = \frac{AW+PWP}{\theta_s}$$

and soil structural stability index (SSI) was computed according to Shehu et al. (2016) as :

$$SSI = \frac{1.724\ x\ OC}{Silt+clay}\ x\ 100$$

In May 2012 (seven months after transplanting) and end of summer of 2012/2013 growing season, tung plant height was measured from the base of the tung tree (soil surface) to the top of the canopy using a steel tape. At the end of the summer of 2013/2014 growing season, tung plant height was measured with the aid of a hypsometer (Model: Vertex IV & Transponder T3, Haglof Sweden AB Inc.). The transponder (sensor) was positioned at about the breast height of the tung tree while the vertex was used to locate the top of the trees and calculate the height of the trees (ALBERTA, 2012). The procedure was done at three representative positions to ensure a good capture of the tung trees. The plant height was saved automatically in the equipment and later downloaded to the computer for further analysis.

The overall SQI was computed using the weighted additive indexing method as described in Tesfahunegn (2014). The scores (VELASQUEZ et al., 2007) of the soil quality indicators were converted into a single values between 0 and 1 (GLOVER et al., 2000).

Principal component analysis (PCA) was used to assess the relationship between the soil variables. This analysis involves extracting principal component factors (PCs) which comprise the soil quality indicators with eigenvalues greater than one (1) using Varimax rotation extraction technique. The relatiocship between variables was based on high factor loading rates of not less than 15% of the highest loading rate from each PC.

Soil physical quality indices, SQI data, and tung plant height were subjected to analysis of variance (ANOVA) and, where F-value was significant, Dunnet's test was used to compare sole tung with other treatments at 5% level of probability. T-test was used to compare PM and NPK fertilizer as well as difference in soil quality indicators between 0 - 10 cm surface and 10 - 20 cm subsurface layers. The statistical analyses were performed in Statistical Package for Social Sciences (*SPSS, IBM Statistics version 20*) and Excel®.

RESULTS AND DISCUSSION

Shortly before intercropping of the cover crops in 2012, Ksat was significantly ($p < 0.05$) highest in the 0 - 10 cm surface layer. Although the average values of Ksat were within the lower (10^{-4} cm s^{-1}) and upper (10^{-2} cm s^{-1}) limits, but are below the upper optimum (0.005 cm s^{-1}) (Figure 2a). Soil BD ranged between 1.52 and 1.58 g cm^{-3}, the 0 - 10 cm surface layer having the lowest value, but this did not differ ($p > 0.05$) from other layers. The BD values were below the lower (1.75 g cm^{-3}) and upper (1.88 g cm^{-3}) thresholds for soil compaction and impedance to root growth, respectively (Figure 2b). Soil AW was not different ($p > 0.05$) among the soil layers although the surface layer presented the lowest AW. The AW was not limited as average values are above the 0.10 cm^3 cm^{-3} considered as a poor state, but were below the ideal condition (AW = 0.20 cm^3 cm^{-3} (Figure 2c).

Soil AC was significantly ($p < 0.05$) highest in the 0 - 10 cm surface layer and decreased with soil depth. The surface layer could slightly present a condition considered adequate for aeration (AC = 0.14 cm^3 cm^{-3}), while the 20 - 40 cm deeper layer showed poor aeration condition (AC < 0.09 cm^3 cm^{-3}) (Figure 2d). Soil relative field capacity, RFC, of the soil layers differed ($p < 0.05$), with the surface layer giving the lowest value, indicating some limitation for water storage. Conversely, the 20 - 40 cm deeper layer showed a limitation to air storage and exchange as already revealed by the AC (Figure 2e). Similarly, the AC/Pt ratio differed ($p < 0.05$) among the soil layers with the trend showing a reserve order compared with the RFC. Although the surface layer had high AC/Pt ratio, but the values were still below the 0.34 designated ideal for near-surface optimum ration for biological activity (Figure 2f).

Soil OC significantly differed ($p < 0.05$) between the two soil layers, and the average values were just above the 0.6% lower limit (figure 2g). Similarly, the 0 - 10 cm surface layer had a significantly ($p < 0.05$) higher TN compared to the 10 - 20 cm subsurface layer.

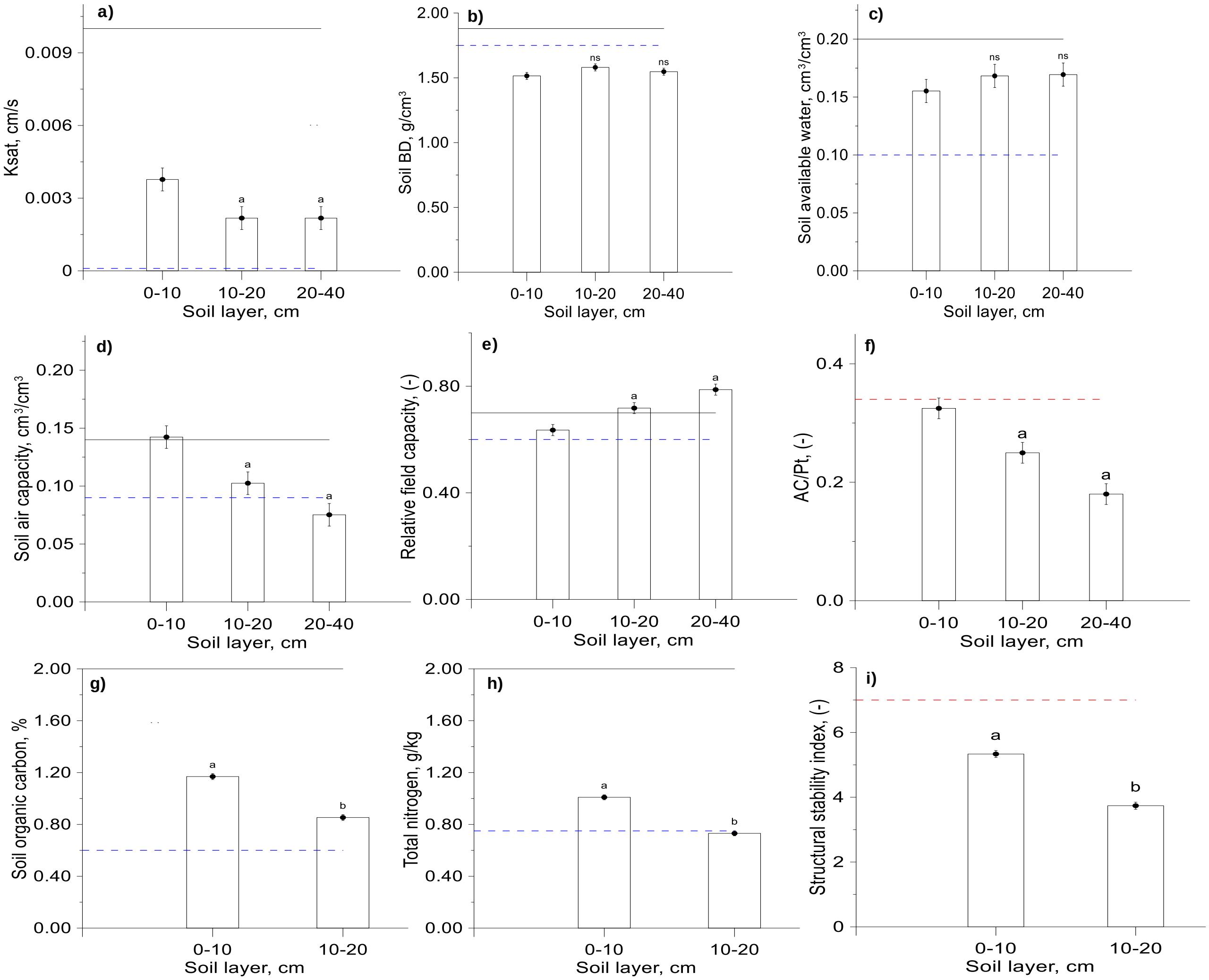

Figure 2. Soil quality indicators of a) saturated hydraulic conductivity, b) bulk density, c) available water, d) air capacity, e) relative field capacity, f) air capacity/field capacity, g) soil organic carbon, h) total nitrogen, and i) soil structural stability index of the tung-based agroforestry field in 2012 shortly before the imposition of the annual cover crops.

The blue dash line is the lower limit (except BD), solid line is the upper limit, while the red dash line is the ideal value for the respective parameters. The vertical line bars are the standard error of the mean. Bars with letters a and b showed significant differences among the soil layers at 5% probability level by Dunnet's test and t- test; ns: not significant.

Surface layer had average TN just above the 0.75 g kg^{-1} lower limit while the surface layer had TN marginally equal the lower limit (Figure 2h). Soil SSI was significantly ($p < 0.05$) higher in the surface layer compared with the subsurface layer, and the average values were below the 7% threshold (Figure 2i).

Soil Ksat of the 0 - 10 cm surface layer was influenced ($p < 0.05$) by cover crops in both growing seasons, with system Tung+Ot/V/PN having the highest value. The Ksat increased in 2012/2013 growing season, while it decreased in 2013/2014 growing season by 57, 23, and 71% in Tung+Cr/Su/So, Tung+Ot/V/PN, and sole tung, respectively with respect to the initial values. Similar trend was observed in the subsurface layers, and the average values were still below the upper threshold of 0.01 cm s^{-1} (Figure 3).

Soil BD of the surface layer differed ($p < 0.05$) and decresed over the years and at the end of the second growing season, the average BD decreased by about 7 and 3% in Tung+Cr/Su/So and Tung+Ot/V/PN systems, respectively, while it increased by 2% in sole tung. The BD of the 10 - 20 cm layer increased whereas it decreased in the 20 - 40 cm deeper layer in all systems (Figure 3). In these subsurface layers, the BD did not differ and the average values were also below the lower threshold (1.75 g cm^{-3}) (Figure 3).

Soil AW of the surface layer was influenced by cover crops, increased in both growing seasons, with system Tung+Ot/V/PN having the significantly ($p < 0.05$) highest value. At the end of the second growing season, AW had increased by 0.5 and 0.78% respectively in Tung+Cr/Su/So and Tung+Ot/V/PN, although the increase was more in the first growing season. In contrast, AW decreased by about 6.8% in sole tung. Significant differences ($p < 0.05$) were recorded in the subsurface layer only at the end of the second growing season, and sole tung had high AW values compared with other systems. In general, the AW of the surface layer was greater than 0.15 cm^3 cm^{-3} although this is still below the ideal condition (Figure 3).

Soil AC differed significantly ($p < 0.05$) due to cover crop intercropping in all the soil layers in both growing seasons. In the 0 - 10 cm surface layer, systems Tung+Cr/Su/So and Tung+Ot/V/PN had the higher AC compared with sole tung. At the end of the second growing season, AC had increased by about 14 and 0.2% respectively in Tung+Cr/Su/So and Tung+Ot/V/PN, while it decreased by 12% in sole tung compared with the initial values in 2012. Soil AC reduced in the 10 - 20 cm layer, whreas it increased in the 20 - 40 cm deeper layer. Sole tung and the two subsurface layers had improve AC values, but were still below 0.14 cm^3 cm^{-3} lower limit for adequate aeration (Figure 4).

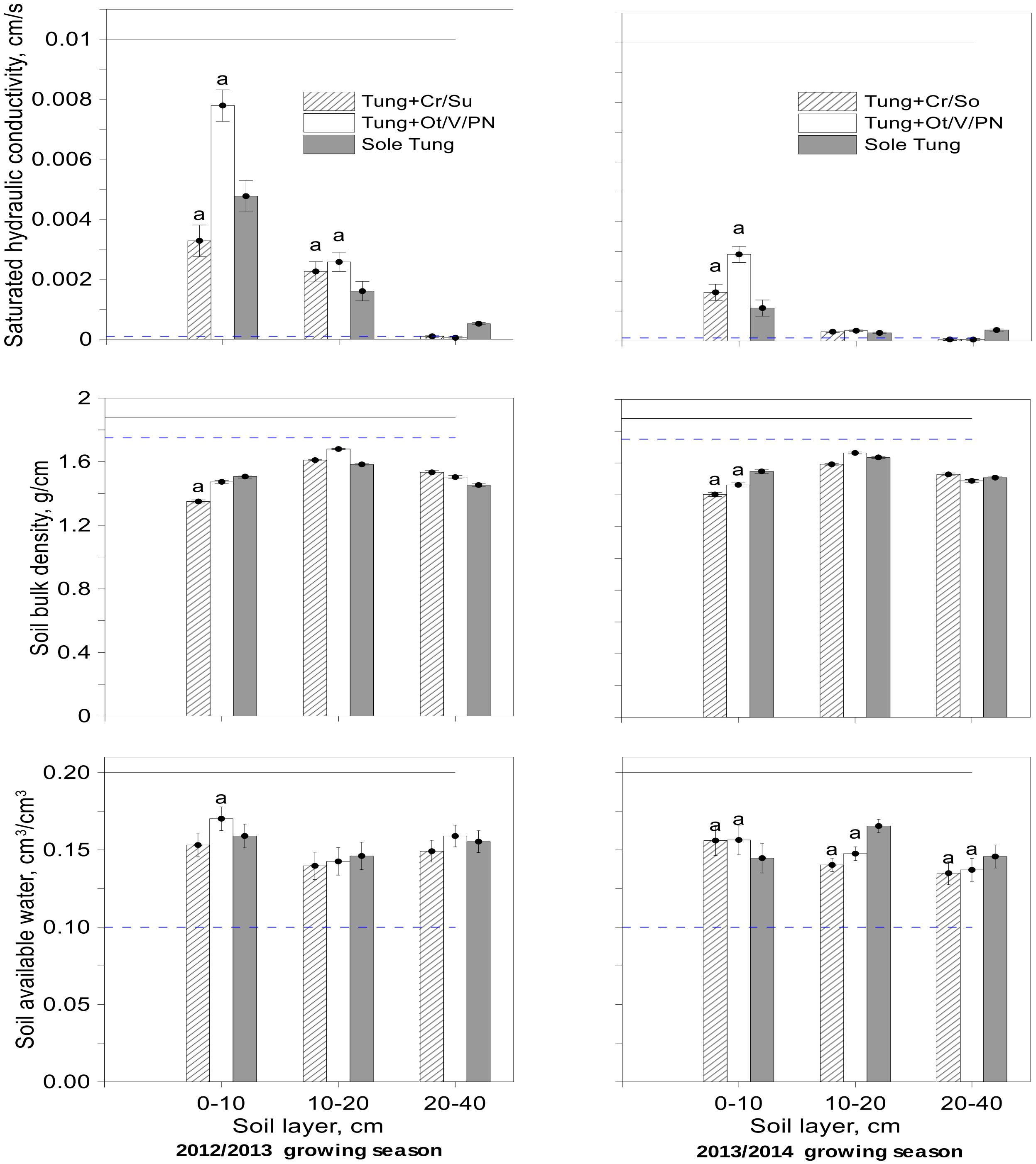

Figure 3. Soil quality indicators of saturated hydraulic conductivity, bulk density, and available water, of the tung-based agroforestry field at harvest of 2012/2013 and 2013/2014 growing seasons.

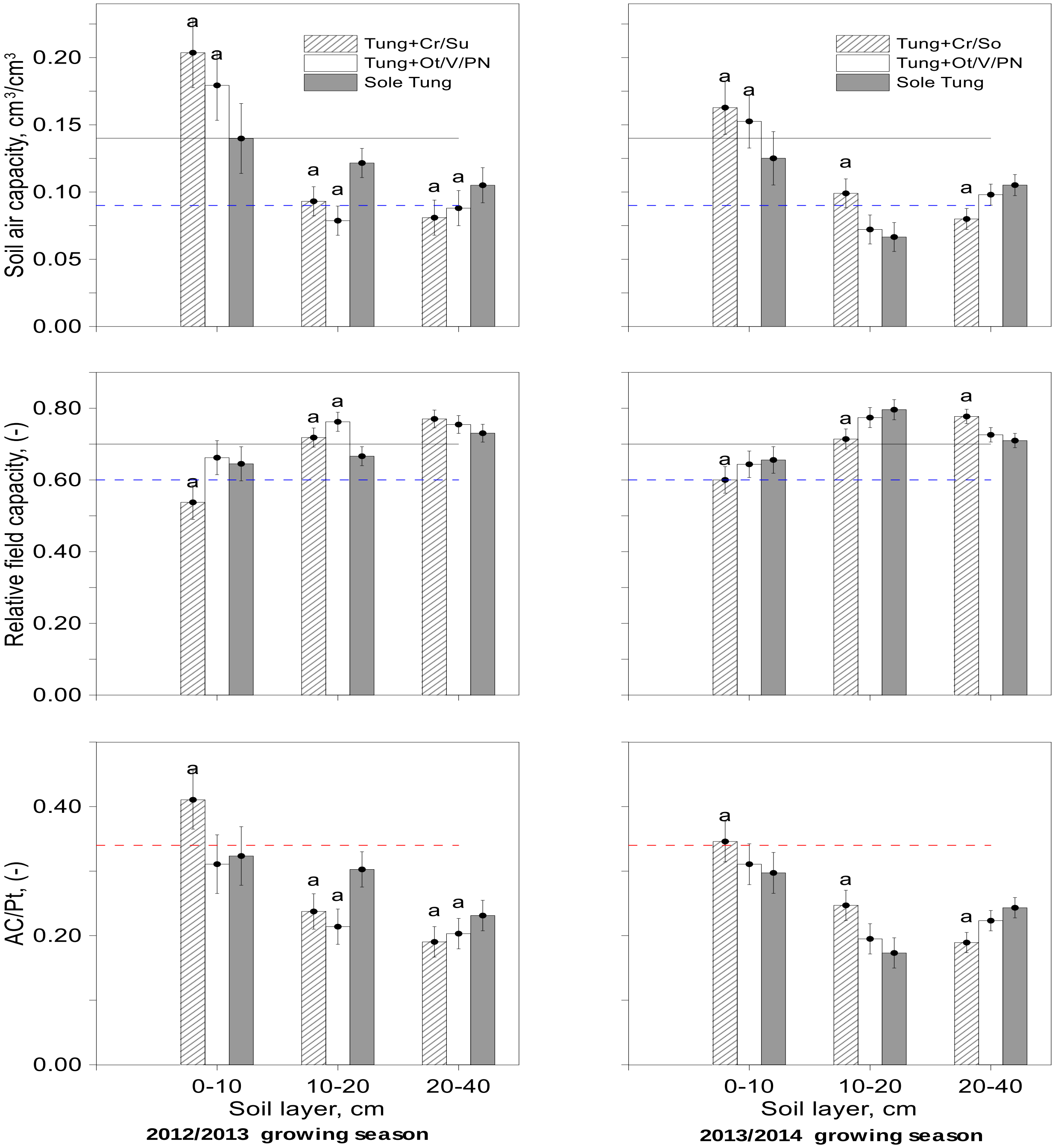

Figure 4. Soil quality indicators of air capacity, relative field capacity, and air capacity/field capacity ratio of the tung-based agroforestry field at harvest of 2012/2013 and 2013/2014 growing seasons.

The blue dash line is the lower limit (except BD) and solid dark line is the upper limit for the respective parameters. The vertical line bars are the standard error of the mean. Bars with letter ‘a’ showed significant differences between sole tung and cover crop treatments at 5% probability level by Dunnet’s test.

Soil RFC of the two layers differed significantly ($p < 0.05$) among the agroforestry systems in both growing season. In the first growing season, Tung+Cr/Su/So system had the lowest RFC, whereas it was sole tung that gave the highest values in the second growing season. The 20 - 40 cm deeper layer had sole tung with the lowest RFC, although the difference was only significant at the end of the second growing season. The 0 - 10 cm surperficial layer had RFC less than 0.6 at the end of both growing seasons, whilst the subsurface layers had RFC greater than 0.7 at the end of the second growing season (Figure 4).

The AC/Pt ratio was influenced by agroforestry system in all the soil layers and growing seasons. In the surface layer, Tung+Cr/Su/So system had the highest value (≥ 0.34) compared with other systems. At the end of the second growing season, Tung+Cr/Su/So system has AC/Pt increased by about 6.5% while it decreased by 8% in sole tung (Figure 4).

Soil OC of the surface layer differed significantly ($p < 0.05$) due to agroforestry system during the two growing seasons. While the average OC of this layer decreased by about 2% in the first growing season, it increased by about 5% at the end of the second growing season from plots with cover crops, while it decreased from sole tung consecutively for the two growing seasons. The subsurface layer had lower OC and only differ among the systems at the end of the second growing season. Despite the increase in OC, the average values were still below the 2% limit in both layers. The same trend was observed for the TN (Figure 5).

Soil SSI significantly ($p < 0.05$) increased due to agroforestry system in both growing season, with systems with cover crops having higher SSI compared with sole tung. The Tung+Ot/V/PN had SSI close to the 7% threshold, while that of sole tung decreased further (Figure 5).

Comparing the effect of poultry manure on the soil quality indicators, significant difference ($p < 0.05$) due to PM was observed for Ksat only in the surface layer and second growing season. However, higher BD, AW, RFC, OC, TN, and SSI while lower AC and AC/Pt were recorded from the surface layer of PM soils compared with NPK soils (Table 2).

The blue dash line is the lower limit, the solid dark line is the upper limit, and the red dash line is the ideal value for the respective parameters. The vertical line bars are the standard error of the mean.

Bars with letter ‘a’ showed significant differences between sole tung and cover crop treatments at 5% probability level by Dunnet’s test.

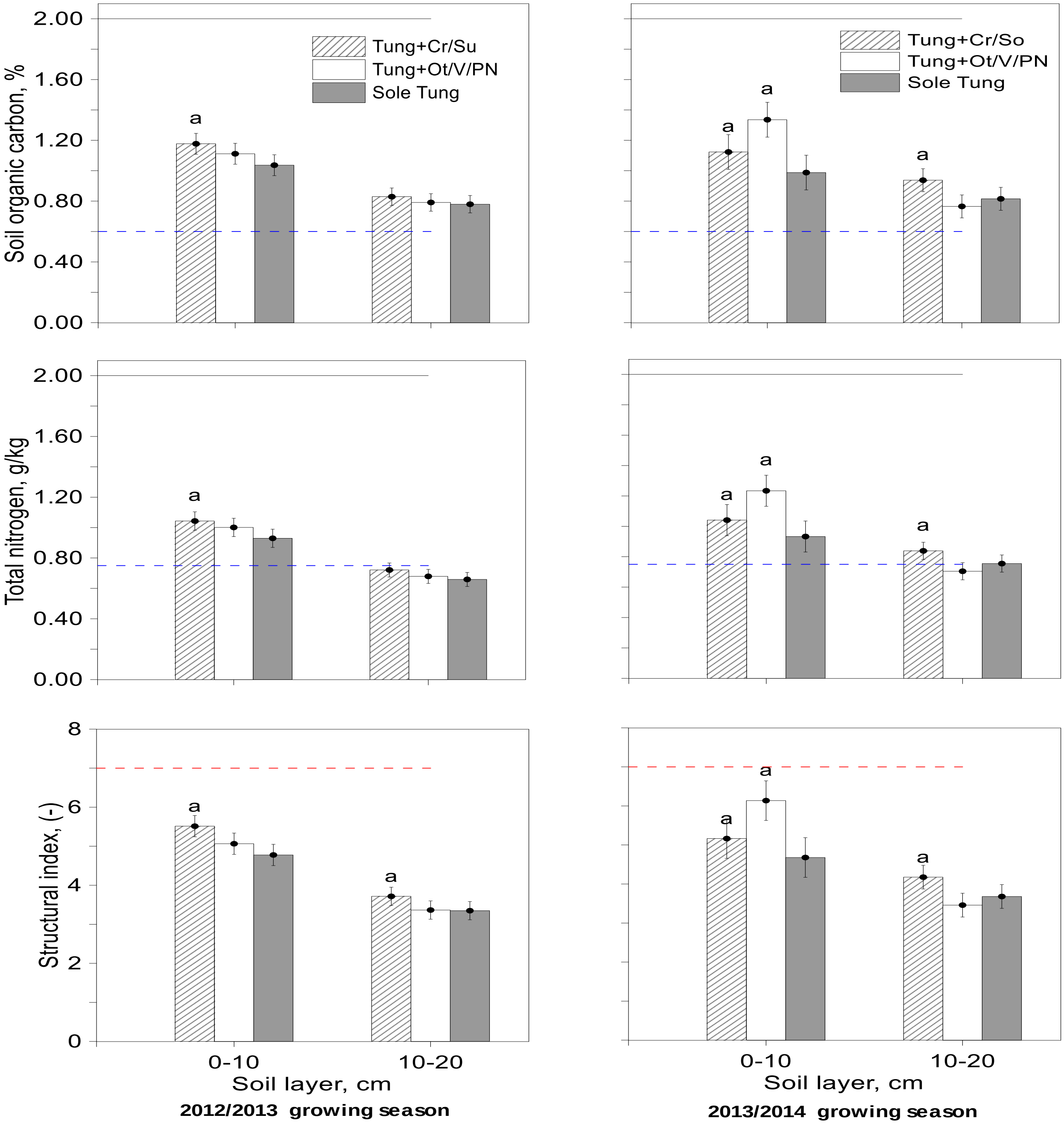

Figure 5. Soil quality indicators of soil organic carbon, total nitrogen, and soil structural stability index of the tung-based agroforestry field at harvest of 2012/2013 and 2013/2014 growing seasons.

The blue dash line is the lower limit, the solid dark line is the upper limit, and the red dash line is the ideal value for the respective parameters. The vertical line bars are the standard error of the mean. Bars with letter ‘a’ showed significant differences between sole tung and cover crop treatments at 5% probability level by Dunnet’s test.

Table 2. Effect of poultry manure (PM) and NPK fertilization on soil quality indicators of the tung-based agroforestry system.

Soil quality indicators	Soil depth, cm	2013		2014	
		NPK	PM	NPK	PM
Ksat	0-10	0.00328	0.00322	0.00163a	0.00059b
	10-20	0.00226	0.00122	0.00031	0.00011
	20-40	0.0001	0.00029	0.00005	0.00042
BD	0-10	1.35	1.48	1.40	1.49
	10-20	1.61	1.64	1.59	1.62
	20-40	1.53	1.55	1.53	1.50
AW	0-10	0.153	0.147	0.156	0.157
	10-20	0.140	0.134	0.140	0.152
	20-40	0.149	0.157	0.135	0.160
AC	0-10	0.204	0.154	0.163	0.138
	10-20	0.093	0.088	0.099	0.098
	20-40	0.081	0.092	0.080	0.100
RFC	0-10	0.538	0.623	0.600	0.635
	10-20	0.718	0.731	0.714	0.717
	20-40	0.770	0.737	0.777	0.732
AC/Pt	0-10	0.411	0.342	0.346	0.315
	10-20	0.237	0.231	0.247	0.250
	20-40	0.190	0.219	0.189	0.229
OC	0-10	1.177	1.143	1.123	1.403
	10-20	0.829	0.790	0.938	0.818
TN	0-10	1.043	1.032	1.041	1.277
	10-20	0.721	0.676	0.839	0.737
SSI	0-10	5.51	5.18	5.16	6.48
	10-20	3.72	3.47	4.18	3.58

Ksat: saturated hydraulic conductivity, cm/s, BD: bulk density, g/cm^3, AW: available water, cm^3/cm^3, AC: air capacity, cm^3/cm^3, RFC: relative field capacity, AC/Pt: ratio air capacity/total porosity, OC: organic carbon, %, TN: total nitrogen, g/kg, SSI: structural stability index, %

The different lowercase letters in a row show significant difference ($p < 0.05$) between NPK fertilizer and poultry manure by t-test.

Tables 3 and 4 show the results of the FA analysis for the two soil layers in 2012 and at the end of the two growing seasons. For the surface layer, 3, 3, and 4 principal components (PCs) were extracted and the first two PCs accounted for about 77, 68, and 81% of the total variance explained by the PCA in 2012, 2012/2013, and 2013/2014 growing seasons, respectively. In 2012, BD, Pt, Ma, Mi and FC in PC1, SOM, TN, and Cpool in PC2, while only C/N in PC3 are the properties with high loading rates. In 2012/2013 growing season, BD, Pt, and Ma in PC1, SOC, TN, and

Cpool in PC2 while Mi, FC, and AW in PC3 are the properties with high loading rates. In 2013/2014 growing season, the first three PCs had the same properties with high loading rate as the previous season while the fourth PC had C/N as the only property with high loading rate. Soil BD showed strong and indirect relationship with Pt and Ma, while the relationship was direct with Mi and FC. The SOC and TN showed a strong and direct relationship, whereas the relationship between AW versus Mi and FC was also direct (Table 3).

For the subsurface layer, 3 - 4 PCs were extracted and the first two PCs accounted for about 67, 65, and 77% of the total variance explained at initial and end of the two consecutive growing seasons, respectively. In addition to the soil properties selected for the surface layer, Ksat was considered by having a high loading rates at the end of the two growing seasons evaluated (Table 4).

Within the confines of the measured soil propeeties, Table 5 shows the SQI of the juvenile tung-based agroforestry system intercropped with cover crops and additional organic manure. At initial, the average values of SQI of the surface layer did not differ significantly ($p > 0.05$) between the tung plots with cover crops, however, SQI significantly differed ($p < 0.05$) between sole tung and systems with cover crops at the end of the two consecutive growing seasons. Furthermore, the SQI of this surface layer of systems with cover crops increased over the years and at the end of the second growing season, SQI increased by 14 and 23% in Tung+Cr/Su/So and Tung+Ot/V/PN, respectively, while the sole tung system had SQI decreased by about 13%. For the subsurface layer, SQI only differed ($p < 0.05$) between sole tung and Tung+Cr/Su/So systems at the end of the second growing season. The subsurface layer had a significantly ($p < 0.05$) lower SQI compared with the surface layer at initial and end of the two consecutive growing seasons.

The application of poultry manure showed higher SQI in the surface layer compared with NPK, but the difference was not significant ($p > 0.05$). In the subsurface layer, a contrasting result was observed as NPK plots had higher SQI, the difference was also not significant (Table 5).

Table 3. Rotated factor loadings and communalities of the management soil quality indicators of the 0-10 cm surface layer of the tung-based cropping system at initial (May 2012) and after each of the 2012/2013and 2013/2014 growing seasons.

	2012				2012/2013				2013/2014				
Soil	--------------PC-------------				--------------PC-------------				---------------------PC------------------				
Par.	1	2	3	Com	1	2	3	Com	1	2	3	4	Com
Ksat	-0.741	0.162	-0.035	0.577	-0.103	0.650	-0.144	0.453	0.490	-0.444	-0.066	-0.280	0.520
BD	0.894	0.364	-0.135	0.950	-0.985	-0.091	-0.023	0.979	-0.971	-0.042	-0.158	0.061	0.973
Pt	-0.908	-0.278	0.149	0.924	0.946	0.175	0.177	0.956	0.950	0.151	0.202	-0.042	0.968
Ma	-0.941	-0.287	-0.066	0.971	0.820	0.096	-0.401	0.842	0.938	0.077	-0.261	-0.061	0.958
Mi	0.781	0.236	0.535	0.952	0.227	0.123	0.865	0.814	0.005	0.154	0.980	0.043	0.986
FC	0.779	0.300	0.494	0.940	-0.450	0.304	0.795	0.926	-0.103	0.261	0.957	0.020	0.994
PWP	0.534	0.736	0.026	0.828	-0.720	0.572	0.196	0.884	-0.453	0.385	0.272	0.616	0.808
AW	0.680	-0.108	0.650	0.896	0.006	-0.079	0.937	0.884	0.224	-0.006	0.824	-0.434	0.917
TN	-0.009	0.971	0.166	0.970	0.326	0.905	0.212	0.970	0.171	0.956	0.155	-0.036	0.968
SOM	0.016	0.980	-0.032	0.963	0.279	0.897	0.299	0.972	0.175	0.950	0.177	-0.147	0.985
CN	-0.132	0.073	0.866	0.773	0.192	-0.232	-0.751	0.654	0.006	-0.260	-0.241	0.792	0.752
Cpool	0.512	0.845	0.047	0.978	-0.082	0.951	0.210	0.956	-0.108	0.972	0.086	0.000	0.963
Eigen	6.76	2.46	1.51		4.53	3.65	2.11		4.17	3.49	2.11	1.02	
Var, %	56.32	20.48	12.55		37.73	30.42	17.61		34.77	29.08	17.55	8.54	
Cum, %	56.32	76.80	89.35		37.73	68.15	85.75		34.77	63.85	81.39	89.93	

Soil Par: soil parameters; PC: principal component; Com: communality values; Ksat: soil saturated hydraulic conductivity, mm/hr; OM: organic matter, %; Cpool: soil organic carbon density, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: soil bulk density, g/cm3; Pt: total porosity, cm3 cm-3; Ma: macroporosity, cm3 cm-3; Mi: microporosity, cm3 cm-3; FC: field capacity, cm3 cm-3; PWP: permanent wilting point, cm3 cm-3; AW: available water capacity, mm. Eigen: eigenvalues; Var.: variance explained by each parameter, %; Cum: cumulative variance explained.

*Values in bold in each PC column were used to select the minimum data set (MDS).

Table 4. Rotated factor loadings and communalities of the management soil quality indicators of the 10-20 cm layer of the tung-based cropping system at initial (May 2012) and after each of the 2012/2013and 2013/2014 growing seasons.

	2012					2012/2013					2013/2014			
Soil	-------------------PC---------------					-------------------PC---------------					------------PC-----------			
Par.	1	2	3	4	Com	1	2	3	4	Com	1	2	3	Com
Ksat	0.326	.111	-.232	.650	.595	-.101	-.124	-.006	-.955	.937	-.546	.232	0.625	.743
BD	-0.476	-0.001	-0.855	-0.028	0.959	0.093	-0.874	0.034	-0.049	0.776	0.431	-0.734	-0.344	0.843
Pt	0.799	0.003	0.588	0.084	0.991	-0.006	0.949	-0.008	0.122	0.916	-0.086	0.882	0.193	0.822
Ma	-0.098	-0.109	0.981	0.057	0.987	-0.254	0.862	-0.392	-0.006	0.962	-0.623	0.702	-0.103	0.892
Mi	0.985	0.082	-0.027	0.056	0.981	0.509	-0.199	0.787	0.213	0.963	0.894	-0.081	0.392	0.959
FC	0.975	0.121	0.076	0.087	0.978	0.445	-0.245	0.777	0.285	0.942	0.929	-0.164	0.273	0.964
PWP	-0.072	0.903	-0.192	0.007	0.858	0.745	-0.469	-0.124	0.294	0.876	0.799	0.367	-0.189	0.809
AW	0.985	-0.026	0.110	0.030	0.984	-0.393	0.279	0.813	-0.060	0.897	0.411	-0.604	0.565	0.852
TN	0.174	0.943	0.140	0.205	0.981	0.979	0.050	0.053	0.064	0.968	0.700	0.684	-0.050	0.961
SOM	0.202	0.944	0.050	-0.160	0.960	0.945	-0.025	0.290	-0.042	0.979	0.809	0.467	-0.100	0.882
CN	-0.077	-0.011	0.239	0.883	0.843	-0.076	0.295	-0.772	0.352	0.814	-0.183	0.821	0.166	0.735
Cpool	-0.202	0.768	-0.555	0.174	0.968	0.948	-0.209	0.047	0.045	0.946	0.807	0.532	-0.120	0.949
Eigen	4.56	3.53	1.74	1.25		5.28	2.46	2.17	1.07		5.18	4.04	1.19	
Var, %	37.98	29.45	14.53	10.41		43.99	20.52	18.08	8.88		43.15	33.65	9.95	
Cum, %	37.98	67.43	81.97	92.38		43.99	64.51	82.59	91.47		43.15	76.81	86.76	

Soil Par: soil parameters; PC: principal component; Com: communality values; Ksat: soil saturated hydraulic conductivity, mm/hr; OM: organic matter, %; Cpool: soil organic carbon density, Mg/ha; TN: total nitrogen, g/kg; C/N: carbon to nitrogen ratio; BD: soil bulk density, g/cm3; Pt: total porosity, cm3 cm-3; Ma: macroporosity, cm3 cm-3; Mi: microporosity, cm3 cm-3; FC: field capacity, cm3 cm-3; PWP: permanent wilting point, cm3 cm-3; AW: available water capacity, mm. Eigen: eigenvalues; Var.: variance explained by each parameter, %; Cum: cumulative variance explained.
*Values in bold in each PC column were used to select the minimum data set (MDS).

Table 5. Overall soil quality index (SQI) of the tung-based agroforestry system with winter and summer cover crops and fertilization.

Treatments		2012	2013	2014
		0-10 cm		
Cover crops	T+Cr/Su/So	0.432	0.497a	0.492a
	T+Ot/V/PN	0.406	0.435a	0.499a
	Sole tung	0.418	0.402	0.363
	Average	0.418A	0.445A	0.451A
Fertilization	NPK	0.432	0.497	0.492
	PM	0.431	0.502	0.506
		10-20 cm		
Cover crops	T+Cr/Su/So	0.355	0.302	0.335a
	T+Ot/V/PN	0.345	0.281	0.262
	Sole tung	0.333	0.298	0.285
	Average	0.344B	0.294B	0.294B
Fertilization	NPK	0.355	0.302	0.335
	PM	0.358	0.288	0.299

T+Cr/Su/So: tung + crambe followed by sunflower (summer of 201/2013) and soybean (summer of 2013/2014); T+Ot/V/PN: tung + mixture of oats and vetch followed by peanut; NPK: inorganic fertilizer; PM: poultry manure. Mean values in a column followed by lowercase letters differed significantly from the control (sole tung) at 5% level of probability by Dunnet test. The different uppercase letters in a column show significant difference ($p < 0.05$) between the surface and subsurface layers by t-test.

Tung growth in terms of plant height at the beginning of the experiment in May 2012 and the end of two consecutive growing seasons are shown in Figure 6. At the imposition of the agroforestry systems (May 2012), the tung plant had equal height, about 1.4 m high, in all the plots. At the end of the 2012/2013 growing season, the agroforestry system did not influence ($p < 0.05$) the increase in tung plant height, although the average plant height had increased between 85 and 100% compared to the initial period, with the lowest growth rate from sole tung. At the T1: tung-crambe-sunflower/soybean rotation+nitrogen fertilizer (T+Cr/S/So+N); T2: tung-crambe-sunflower/soybean rotation+poultry manure (T+Cr/S/So+N); T3: tung-oats/vetch-peanut rotation (T+Ot/V/P); T4: sole tung (control). ns: not significant at 5% level of probability by Fisher's Least square difference (LSD) test.

End of the second growing season, tung plant height increased further by 50%, although the differences among the treatments were not significant ($p < 0.05$).

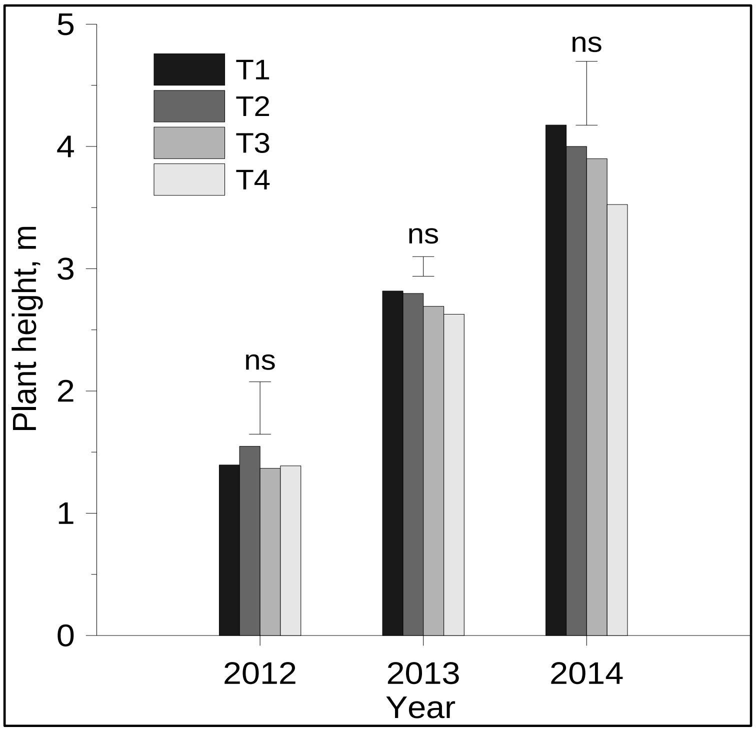

Figure 6. Average values of tung plant height at the beginning, in May 2012, and end of summer period 2012/2013 and 2013/2014 growing seasons, respectively.

Agroforestry soil conditions are affected by soil gaseous, liquid, and solid phases. A balanced ratio of these three parts is an indication that the soil properties and processes would be suitable for the growth of the tree component as well as the companion crops. Soil OC affects nearly all vital properties and processes that contribute to soil functioning and productivity (BENNETT et al., 2010). The reduced soil OC content of the 0 - 10 cm surface layer in the first year of evaluation may be due to carbon loss as carbon dioxide from this soil as a result of soil mobilization done shortly before transplanting. The sandy nature of the soil indicates a well-drained structure and possibly, the organic carbon of the surface layer becomes easily oxidized. In plots with cover crops where the soil OC was expected to increased, the reduction in OC could be due to soil sampling done shortly before harvest while spreading of the plant residues was done thereafter. Besides there could be a little contribution from the limited litter on the surface as well as from the roots which are still active at the time of sampling.

At the end of the second growing season, soil OC has improved due to the presence of plant residues on the soil surface and decayed roots in this layer, this increased biological activity as decay and decomposition processes continue (WEILER et al., 2019). Balbinot Junior et al. (2011)

and Demir et al. (2019) reported that intercropping cover crops yields a greater amount of biomass; thus, a high accumulation of total and particulate organic carbon on the soil surface. The increased OC has positive effect on nutrients storage and cycling, majorly nitrogen, plant available water, pore space, aggregation and stability of aggregates (SILVA & SA-MENDONCA, 2007). The differences observed between the cover crops may be attributed to the amount and speed of decomposition which vary according to the residue C/N ratio (Rehm, 2010). The lower soil OC in sole tung and in the subsurface layer is attributed to low accumulation of biomass in the surface layer of the sole tung and in the subsurface layer, evidencing lesser biological activity.

Shorthly before intercropping of the cover crops, the higher BD in the subsurface layer compared with that of the surface layer may be due to effect of overlying layer and previous management practices such as tillage machine traffic before transplanting of tung. The reduced BD in the surface layer of tung + cover crops could be the beneficial effects of the cover crops on soil structure, such as improved soil aggregation and increased pore space due to increased biological activity from accumulation of plant residues on the surface layer. Haruna and Nkongolo (2015) found that rye cover crop significantly reduced BD by about 3.5% compared with no-cover crop plots. Similar reduction in BD in the surface layers of soils with incorporation of cover crops to production systems have been reported (NASCENTE & STONE, 2018; DEMIR & ISIK, 2019A, 2019B; DEMIR et al., 2019). The mechanism explaining this is that the decomposing organic matter is less dense compared with the mineral consituents, leading to reduced density (PORTELLA et al., 2012).

Although the average values of BD of the 10 - 20 cm subsurface layers were significantly higher than those of the surface layer in both seasons, the values were below 1.75 g cm^{-3} considered as the threshold. According to Collares et al. (2006) and Reichert et al. (2009), soils with BD values beyond this limit exploring deeper layers for water and nutrients by plant root during periods of low rainfall as well as negatively influence water dynamics and gaseous exchange, especially during periods of heavy rainfall.

The greater initial soil Ksat in the surface layer could be as a result of soil tilling before transplanting of tung. The tilled layer is characterized by breaking down soil clods, reducing the bulk density and increasing pore volume responsible for water movement. Conversely, the lower initial soil Ksat observed in the subsurface layers is attributed to the high BD and low porosity in these layers. The higher soil Ksat values of the surface layer in systems with cover crops at harvest of both growing seasons is as a result of the beneficial effects of the cover crops. Soil Ksat is a highly variable, dynamic and complex property whose behavior is highly affected by soil compaction (REICHERT et al., 2007), a process that highly impacts soil pore geometry responsible for water, air, and solute movement (BORMANN & KLAASSEN, 2008; HU et al., 2009; MESQUITA & MORAES, 2004). Therefore, measures are required to decrease soil compaction and increase or maintain soil pore space through increased biological activity by increasing SOC. Furthermore, the creation of biopores by the cover crop root systems could have paved way for enhanced water flow (ABREU et al., 2004). Researchers have reported increased Ksat due to cover crops in orhards (DEMIR & ISIK, 2019A; DEMIR et al., 2019). Conversely, the reduced soil Ksat in the 0 - 10 cm surface layer of sole tung plot is as a result of low porosity and elevated BD resuçting from raindrop impact and soil reconsolidation. It is worthy to note that the sandy texture of this bare layer could be another contributing factor as soil aggregates are easily detached by raindrop impact, and during infiltration, large pores are blocked by the detached particles, thus reducing soil Ksat (REICHERT & NORTON, 1995; REICHERT & NORTON, 1996; ZEJUN ET AL., 2002), whereas cover crops increase the stability of soil aggregates by proctecting the soil surface from raindrop impact (Blanco-Canqui et al., 2015).

The low Ksat from the subsurface layers of all the treatments is also related to the increased BD and reduced macropore volume as observed in these layers. The reduced macropore indicates more intermediate and micropores which present low contribution to flow, hence the reduction in Ksat. Surprisingly, the reduced Ksat at the end of the second growing season compared with the first growing season is attributed to the complex nature of Ksat. Even in the surface layer where the BD was reduce and porosity was increased due to increased biological activity, the Ksat was reduced. Possible reasons for this could be the soil condition at sampling, sampling location, and the presence of special pores such as earthworm burrows, large roots, and buried objects.

Clay content and organic carbon are the major factors influencing PWP and FC used to compute plant available water (AW) (GULSER & CANDEMIR, 2015; REYNOLDS et al., 2002;). Greater amount of organic matter was reported to increase FC and PWP (DA COSTA ET AL., 2013; REICHERT et al., 2009; REICHERT et al., 2020;). While the FC is affected by management, especially practices that increase or decrease soil organic carbon, especially in sandy-textured soils (Bauer & Black, 1992), the PWP on the other hand is controlled by texture mainly the clay content, which is not affected by management practices. In this study, the higher OC in plots with cover crops resulted in higher AW compared with sole tung. Basche et al. (2016) found that winter cover crop increased the AW of a maize-soybean rotation by 21 - 22%. The authors attributed the increase in AW to increased soil OC which increased the FC. Demir et al. (2019) also reported an increase in the AW of an apricot orchard by about 19% due to incorporation of cover crops. However, Nascente & Stone (2018) observed decrease in AW in the surface layer after a two-year study of the effect of cover crops on soil physical and chemical properties of rice-soybean rotation. They attributed the effect to the complex interaction among density, clay content, and soil organic matter and the alterations in the factors which strongly influence the FC.

The relatively lower AW in the 10 - 20 cm subsurface layer may be due to the greater BD and lower OC in this layer. Soils with high BD means densed or compacted structure with closer particle-to-particle contacts which reduces water films between soil particles (ZHAO et al., 2017). Low OC indicates lower surfaces for water absorption, thus a lower FC and AW. The AW is rated good, but none of the soil layers reached the ideal condition (AW ≥ 0.20 cm^3 cm^{-3}) for optimum root growth and drought resistance (REYNOLDS et al., 2015).

Soil AC is the ability of the soil to make available adequate air for root growth and soil microorganisms. RFC on the other hand shows whether the soil is limted by shortage of soil air (RFC > 0.7; air-limited) or is having problem of inadequate water storage (RFC < 0.6; water-limited) (REYNOLDS et al., 2015). However, a balance between soil air capacity and water storage is required for optimum root growth and development. Thus, Olness et al. (1998) stated that to ensure this optimal balance for the near-surface layer, the ratio AC/Pt should be equal to 0.34. However, these properties are highly dependent on soil pore volume, especially the macropore volume.

The higher AC and lower RFC from plots with cover crops is attributed to increased macropore volume (data not shown) observed which is also linked to the effect of increased OC. The 0.6 < RFC < 0.7 in the surface layer indicates no water storage problem. However, the subsurface layers with RFC > 0.7 indicates an air-limited condition as reflected in the low AC. The decreased AC in the subsurface layers is attributed to elevated BD and decreased porosity. According to Hillel (2004), intermediate pores are higher in compacted soils (soils with high BD) as the large inter-aagregate pores or macropores may have been compressed resulting in limited pores for air flow. Despite the increased AC in the surface layer, the values were still below the

0.20 cm^3/cm^3 considered ideal for ensuring atmospheric concentration of CO_2 and O_2 (REYNOLDS et al., 2015).

The ratio AC/Pt ≈ 0.34 in the surface layer in Tung+Cr/Su/So system indicates an optimal balance for the near-surface soil water holding capacity and aeration. Reynolds et al. (2002) stated that the AC/Pt criteria becomes important under rain-fed crop production systems as soils with values equal to the ratio are likely to posses the desired balance of water and air for optimum production of microbial nitrogen at a more frequent rate and for extended periods, mostly required at the critical early crop growth stage than soils with much higher or lower ratios. Nascente & Stone (2018) found that AC and AC/Pt were still below the recommended levels after two years of cover crops incorporation in upland rice and soybean rotation system.

The higher SSI in plots with cover crops indicates the ability of the soil's resilience to stresses. Several authors have reported the beneficial effects of cover crops on soil structure and stability of aggregates (RILLING et al., 2002; SILVA & MIELNICZUK, 997; TISDALL & OADES, 1979) by accumulated plant residue and high root density, which promotes aggregation of soil particles, emission of soil exudates which stimulate microbial activity, whose by-products act in the formation and stabilization of aggregates (SILVA & MIELNICZUK, 1997). Low SSI in sole tung and the subsurface layers indicates a degrading structure (REYNOLDS et al., 2007). This is attributed to the sub-optimal OC recorded in this system and soil layers, meaning the sole tung soil and sublayers could offer limited resistance when subjected to stresses.

Nitrogen is vital in plant vegetative growht and soil functioning. The plots with cover crops had significantly higher ($p < 0.05$) TN in the surface layer at the end each growing season as a result of increased mineralization of organic matter from the plant residue. Moreover, the more diversity of species in Tung+Ot/V/PN compared with Tung+/Cr/So may have contributed to the feedstock for mineralization. According to Black et al. (2010), more N become available as a result of increased litter for the decomposition process.

Apart from the Ksat, poultry manure did not significantly ($p > 0.05$) influence the soil quality indicators, albeit positive effect on these indicators was observed. For example, the higher TN from the addition of poultry manure could be as a result of mineralization of nitrogen from increased decomposition by the additional organic matter. Jokela et al. (2009) also reported that liquid dairy manure only did not significantly increased soil quality indicators evaluated. In this study, the result may be attributed to the relatively short-term evaluation.

Soil quality index integrates one or several measures of soil physicochemical and biological properties. The SQI obtained in this study are within the range reported in studies on crop-based intercropping and crop rotation (AZIZ et al., 2011; GELAW et al., 2015; SEKER et al., 2017; YAO et al., 2013), which show low to moderate soil quality status. The higher SQI obtained in the surface layer of plots with cover crops at the end of both growing seasons is in line with the results of the soil quality indicators (low BD and RFC, high OC, TN, AW, Ksat, AC, AC/Pt, and SSI).

In agroforestry systems, greater C additions from the residues of various plant species favour soil biodiversity, C sequestration, and indirectly improves soil physical quality and associated ecosystem services (BUCHELI & BOKELMANN, 2017; DE STEFANO & JACOBSON, 2017). Furthermore, the vigorous roots of the cover crops enhances soil aggregation by intertwining particles, root penetration, increase in available water and exudation of humic substances, enhancing the soil physical quality (SIX et al., 2004).

In the subsurface layer, the lower SQI results from elevated BD and lower values of other quality indicators observed. This is not unexpected because the impact of soil conservation strategies such as crop residues retention, crop rotation, cover crops, and soil amendments aimed at improving soil quality is limited to the surface layer. In their studies on the effect of crop rotation on soil quality, Aziz et al. (2011) reported decreased SQI with increasing soil depth. Similarly, Reynolds et al. (2014) reported poor soil physical quality in the subsurface layers and attributed it to possible factors such as poor drainage and aeration problems, a structure that easily crumbles and releases its OC.

The order of the response of the soils in terms of SQI was T+Cr/Su/So ≈ T+Ot/V/PN > sole tung. The implication is that the soil environment of tung + cover crops is aggrading, whereas the sole tung soil is degrading as also revealed by the SSI. Therefore, for the sole tung plots, there is the need for soil and water conservation strategies which the cover crops has shown to proffer.

The addition of poultry manure increased the SQI. Magdoff & van Es (2009) stated that management practices that increase and maintain soil organic matter are the basis for a healthy and functional soil, leading to thriving and manageable agricultural ecosystems.

The taller tung plants from plots with cover crops and additional poultry manure compared with sole tung plant as well as the increased grain yield of the cover crops over the year indicate the beneficial effects of crop residues, roots, and additional poultry manure that are prerequisite for biological activity, mineralization, nutrients cycling for plant growth and productivity. With more organic matter, the soil mineralization process is increased, providing more nitrogen to meet plants need. Similarly, the near-surface layer provided the non water and air limited condition for the optimum production of nitrogen for plant use.

Furthermore, increased OC reduced the BD and improved the pore space, presenting good physical conditions necessary for root growth and increased productivity. Other authors have reported enhanced crop growth and yield due to cover crop and organic amendment (BASCHE et al., 2016; DEMIR & ISIK, 2019A, DEMIR & ISIK, 2019B; DEMIR et al., 2019; NASCENTE & STONE, 2018;). Although the tung plant is yet to fruit as at the time of carrying out these evaluations, however the vigorous growth (several branches) observed in plots with cover crops and additional PM indicates the yield from the amended plots will be greater compared to pure tung stands.

CONCLUSION

The effect of intercropped cover crops and additional poultry manure on soil physical quality indices of a juvenile tung soil environment and crop growth was studied. Cover crops increased soil organic carbon and subsequently improved soil structure by reducing bulk density and relative field capacity, increasing plant available water, saturated hydraulic conductivity, air capacity, air capacity-total porosity ratio, and total nitrogen of the surface layer of the tung-based agroforestry system at the end of the two growing seasons.

The soil quality index of the 0 - 10 cm surface layer of tung plots with cover crops increased over time, while it reduced in unprotected, sole tung. At the end of the second growing season, the soil quality index of the surface layer was in the order: Tung+Crambe/Sunflower/Soybean ≈ Tung+Oat/Vetch/Peanut > sole tung. The soil quality index of the 10 - 20 cm subsurface soil layer did not change during the studied period.

Addition of poultry manure enhanced the soil quality status of the tung field.

Cover crops and additional poultry manure improved tung growth.

The increased organic carbon inputs and improved soil structural condition are the driving forces for the enhanced tung growth in the tung-based agroforestry system.

The short-term effect of cover crop intercropping and organic manure in the tung-based agroforestry system was benefial to both the soil and crop while the unprotected, sole tung soil is degrading. Therefore, the evaluated strategies are advocated for sustaining juveline tree crop plantations and protectiong the environment.

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