SOIL MACROFAUNA ABUNDANCE AND DIVERSITY UNDER TREES WOODLOTS IN EASTERN DEMOCRATIC REPUBLIC OF CONGO †

[ABUNDANCIA Y DIVERSIDAD DE LA MACROFAUNA DEL SUELO BAJO LOTES ÁRBOLADOS EN LA REPÚBLICA DEMOCRÁTICA DEL ESTE DEL CONGO]

Jean-Leon Kataka[1,*], Richard Onwonga[1], Nancy Karanja[1], and Solomon Kamau[1,2]

[1] Department of Land Resource Management and Agricultural Technology (LARMAT), College of Agriculture and Veterinary Sciences, University of Nairobi, P. O. Box 29053-00625, Nairobi, Kenya. E-mail address: jeanleonkataka96@gmail.com
[2] Present address: School of Agriculture and Natural Resources, Moi University, P.O. Box 3900-30100, Eldoret, Kenya.
[*]Corresponding author

SUMMARY

Background. Soil macrofauna are key components of agricultural processes due to their ability to enhance major soil functions such as nutrient cycling and organic matter decomposition. Yet, in the Democratic Republic of Congo, their compositions and dynamics are threatened by the intensification of agricultural activities on small pieces of land characterised by integration of trees into crops farms. **Objective**. To assess the effect of diverse tree species on soil macrofauna abundance and diversity and selected soil chemical properties. **Methodology**. *Eucalyptus saligna* and *Grevillea robusta* woodlots were considered for this study, together with a natural forest, an indigenous tree (*Ficus benghalensis*) and an agricultural farm (with beans grown on it), and were set up as treatments. A complete randomised design was used whereby each treatment was replicated five times in four different locations. Soil macrofauna were collected using soil monoliths as well as Pitfall and Winkler traps, while composite soil samples were taken from monoliths after macrofauna catching. Soil macrofauna were identified at the order level and soil nutrients analysed in the laboratory following standard procedures. The analysis of variance and correlations were carried out using R programming software. **Results**. Soils under natural forest showed significantly low pH as compared to grevillea, eucalyptus, ficus and beans. Soil C levels were significantly low in beans (33.6 g kg-1), than grevillea (45.0 g kg-1), ficus and eucalyptus (46.2 g kg-1 and 47.7 g kg-1), and natural forest (60.7 g kg-1), whereas N was significantly low in beans (3.7 g kg-1) as compared to ficus and eucalyptus (4.3 g kg-1 and 4.7 g kg-1), and grevillea and natural forest (5.3 g kg-1 and 5.3 g kg-1). Soil Ca was significantly higher under ficus, than beans, grevillea, natural forest and eucalyptus. Same trends were observed for P, K and Mg. Highly significant ($p < 0.05$) macrofauna abundance was observed for Araneae (spiders) under beans with an average of 7.3 individuals, compared to grevillea and eucalyptus (6.0 and 5.1 individuals respectively), and natural forest and ficus (3.3 and 2.8 individuals respectively). Inversely, Coleoptera (beetles) were significantly lower under beans than natural forest, ficus, eucalyptus and grevillea, whereas Haplotaxida (earthworms) and Hymenoptera were both higher under ficus. Soils in natural forest and ficus revealed highly significant richness index (9.8 and 9.5) than grevillea and eucalyptus (9.0 and 8.8) and beans (7.5). The Shannon diversity index together with the evenness index were both significantly ($p < 0.05$) higher under beans and lower under ficus. **Implication**. The diversification of soil macrofauna under specific tree species for this study indicates their importance towards the preservation of soil macrofauna communities whose activities impact on soil chemical and physical properties and contribute to maintaining soil ecological functions. **Conclusion**. Thus, in order to maximize positive interactions between tree species, soil macrofauna and soil properties, hence to sustain soil health and maintain a better soil biodiversity, it is important to take into consideration the integration of appropriate tree species into farming systems.
Key words: soil macrofauna; soil chemicals; soil degradation; *Eucalyptus saligna*; *Grevillea robusta*.

RESUMEN

Antecedentes. La macrofauna del suelo es un componente clave de los procesos agrícolas debido a su capacidad para mejorar las principales funciones del suelo, como el ciclo de nutrientes y la descomposición de la materia orgánica. Sin embargo, en la República Democrática del Congo, sus composiciones y dinámicas están amenazadas

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por la intensificación de las actividades agrícolas en pequeñas porciones de tierra caracterizadas por la integración de los árboles en las granjas de cultivo. **Objetivo**. Evaluar el efecto de diversas especies de árboles sobre la abundancia y diversidad de la macrofauna del suelo y las propiedades químicas seleccionadas del suelo. **Metodología**. Para este estudio se consideraron lotes arbolados de *Eucalyptus saligna* y *Grevillea robusta*, junto con un bosque natural, un árbol autóctono (*Ficus benghalensis*) y una finca agrícola (con frijol cultivado en él), y se establecieron como tratamientos. Se utilizó un diseño completamente al azar en el que cada tratamiento se replicó cinco veces en cuatro lugares diferentes. La macrofauna del suelo se recolectó utilizando monolitos de suelo, así como trampas Pitfall y Winkler, mientras que se tomaron muestras compuestas de suelo de monolitos después de la captura de macrofauna. La macrofauna del suelo se identificó a nivel de orden y los nutrientes del suelo se analizaron en el laboratorio siguiendo procedimientos estándar. Los análisis de varianza y correlaciones se realizaron mediante el software de programación R. **Resultados**. Los suelos bajo bosque natural mostraron un pH significativamente bajo en comparación con grevillea, eucalipto, ficus y frijol. Los niveles de C del suelo fueron significativamente más bajos en frijoles (33.6 g kg^{-1}), que en grevillea (45.0 g kg^{-1}), ficus y eucaliptos (46.2 g kg^{-1} y 47.7 g kg^{-1}) y bosques naturales (60.7 g kg^{-1}), mientras que el N fue significativamente bajo en frijol (3.7 g kg^{-1}) en comparación con ficus y eucalipto (4.3 g kg^{-1} y 4.7 g kg^{-1}), y grevillea y bosque natural (5.3 g kg^{-1} y 5.3 g kg^{-1}). El Ca del suelo fue significativamente mayor bajo ficus que frijol, grevillea, bosque natural y eucalipto. Se observaron las mismas tendencias para P, K y Mg. Se observó abundancia de macrofauna altamente significativa ($p<0.05$) para Araneae (arañas) bajo frijol con un promedio de 7.3 individuos, en comparación con grevillea y eucalipto (6.0 y 5.1 individuos respectivamente), y bosque natural y ficus (3.3 y 2.8 individuos respectivamente) . Inversamente, los coleópteros (escarabajos) fueron significativamente más bajos bajo los frijoles que los bosques naturales, ficus, eucaliptos y grevilleas, mientras que Haplotaxida (lombrices de tierra) e Hymenoptera fueron ambos más altos bajo los ficus. Los suelos en bosque natural y ficus revelaron índices de riqueza más significativos (9.8 y 9.5) que los de grevillea y eucalipto (9.0 y 8.8) y frijol (7.5). El índice de diversidad de Shannon junto con el índice de uniformidad fueron significativamente más altos ($p <0.05$) bajo los frijoles y más bajos bajo los ficus. **Implicación**. La diversificación de la macrofauna del suelo bajo especies de árboles específicas para este estudio indica su importancia para la preservación de las comunidades de macrofauna del suelo cuyas actividades impactan en las propiedades químicas y físicas del suelo y contribuyen a mantener las funciones ecológicas del suelo. **Conclusión**. Por lo tanto, para maximizar las interacciones positivas entre las especies de árboles, la macrofauna del suelo y las propiedades del suelo, y por lo tanto para mantener la salud del suelo y mantener una mejor biodiversidad del suelo, es importante tener en cuenta la integración de las especies de árboles apropiadas en los sistemas agrícolas.

Palabras clave: macrofauna del suelo; productos químicos del suelo; degradación del suelo; *Eucalyptus saligna*; *Grevillea robusta.*

INTRODUCTION

Soil biota is considered one of the soil quality indicators as it can be utilised in determining the effects of land management change (Murage *et al.*, 2000; Silva *et al.*, 2011). In any ecosystem, they are key components due to their ability to enhance major soil functions like soil structure conservation, nutrient cycling, and organic matter decomposition (Barrios, 2007). Particularly, soil macrofauna represents a major constituent of the soil biota considering their great role in modifying these soil processes (Lavelle, 1997), such that some of the major groups of soil macrofauna like termites and earthworms are documented as “ecosystem engineers” (Jones *et al.*, 1994). Soil fauna is highly influenced by management practices as well as the vegetation type (Lavelle *et al.*, 1994). It has been shown that soil faunal physiology and their group configuration diverge in soils considering the nature of plant species within a given land cover (Bardgett *et al.*, 1999; Eviner, 2004; Innes *et al.*, 2004). For instance the integration of trees in crop farms, which represent one of the major land use in the agricultural landscapes under the tropics (Zomer *et al.*, 2014), can impact soil functions by acting on determinants such as climatic parameters (moisture and temperature), quality of organic matter produced and edaphic factors and end up by affecting the soil macrofauna (David, 2015). In fact, in their areas of influence, trees act like hotspots of biological activity via recycling of nutrients from soil depth, carbon inputs and safeguarding microclimatic conditions (Barrios *et al.*, 2011). Given their feeding preferences for particular organic substrate categories, distribution of groups of macrofauna in soil can be influenced by the quality of litter and the configurations of its deposition alongside root turnover (Pauli *et al.*, 2010). This is in regard with the fact that together with the shading, they represent factors altering the environment (state of soil moisture, nutrient regimes, carbon availability and temperature) under trees canopy (Lin, 2010). Therefore, plant diversity affects life in the soil. In turn, soil biota manages the decomposition of organic resources together with the synthesis of soil organic matter, alters soil structure, and consequently determines soil nutrient and water availability and, ends up controlling plant growth and community configuration (Bardgett *et al.*, 2005; Van der Putten *et al.*, 2009). Thus, in order to minimize the negative interactions while maximizing the positive ones, it is important for farmers to adopt suitable practices, including the careful choice of type of tree species to intercrop with other cultures, as they might impact either positively or negatively the macrofauna abundance, diversity and distribution, therefore impact on soil properties (Korboulewsky *et al.*, 2016).

In the Democratic Republic of Congo, farmers intercrop trees with annual crops. This is the case of *Grevillea robusta* and *Eucalyptus saligna* trees which have been recognized as the most grown trees on farms, especially in North Kivu province (Geert *et al.*, 2013). They are cultivated mainly for the great role they play in charcoal and firewood production, for increasing good interactions between crops and trees and thus augmenting farms' agricultural productivity, and finally for managing hazards through timber (Geert *et al.*, 2013; He *et al.*, 2015; Nabunya, 2017). Yet where they have been largely grown, these tree species have been acknowledged to have induced change in soil biophysical and chemical properties (Kerkhof, 1990; Zewdie, 2008). This is in addition to the issues of soil fertility depletion, high transpiration rates, interference with biodiversity conservation, and allelopathic impacts constraining undergrowth restoration (Ravina, 2012; Zewdie, 2008) as well as reduction of macrofauna richness (Kamau *et al.*, 2017; Sheila *et al.*, 2016). These phenomena were particularly supported by several authors who found that some intercropped trees, apart from having significant influence on soil physicochemical properties, and soil organic matter content, also impact considerably on the soil macrofauna abundance and diversity (Aweto and Moleele, 2005; Kamau *et al.*, 2017; Tererai, 2012). Kamau *et al.* (2017) found for instance that soil macrofauna, especially earthworms, were intensely lower in *Eucalyptus grandis* trees in comparison to *Zanthoxylum gilletii* and *Croton megalocarpus* trees. Also, while evaluating the levels of organic carbon, Noella *et al.* (2015) reported that the soil under *Grevillea robusta* showed the highest value (3.3%) yet *Leucaena leucocephala* had the least value of 0.84%. In addition, the land scarcity occurring in the region leading farmers to concentrate their activities on small pieces of lands by growing together both trees and agricultural annual crops has ended up accelerating land overexploitation (Ebenezer *et al.*, 2014). This implies the utilization of more inorganic and organic fertilizers and the adoption of farming practices involving the intensification of both mechanical (tillage, etc.) and chemical (fertilizers, etc.) inputs, which have been highly mentioned to provoke modifications on the soil biological properties (soil macrofauna composition), and consequently on soil chemical and physical properties (Ayuke *et al.*, 2011a; Fernandes *et al.*, 1997).

However, despite the fact that the actual significance of these knowledges on soil health and biodiversity has been broadly developed in high-input agriculture in temperate regions, there are limited insights on how these notions apply in the tropics characterized by low-input farming systems (Ayuke *et al.*, 2011b). Although few studies have been conducted in the study region focusing on the stock of carbon and their flux in trees (Katembo, 2017), and some others on the impact of trees growth on soil nutrients and soil erosion (Sahani, 2004), however limited investigation has been committed to interactions between trees and soil macrofauna and soil nutrients. Thus, in a region where people's livelihood mostly depends on agriculture, and given that in Democratic Republic of Congo *Eucalyptus saligna* and *Grevillea robusta* trees constitute the majority of tree species plantations, this study therefore took the lead in assessing their influence on soil macrofauna abundance and diversity, and soil chemical properties (total N and C, soil pH, available P, Ca, Mg and K) in comparison to natural forest, bean crop and ficus trees.

MATERIALS AND METHODS

Description of the study site

This study was carried out in the eastern part of the Democratic Republic of the Congo in North Kivu province. The North Kivu province has a population estimated at 7.5 million and a surface area of 60,000 km^2. It is situated between latitude 0°58' North and 02°03' South and longitude 27°14' West and 29°58' East. The Eastern part borders Rwanda and Uganda (South-East), the North-west by the Ituri province, the South-West by the Maniema province, and the South by the South-Kivu province (Muvunga, 2019). North Kivu province presents a topography at an altitude ranging from 800 m to 2,500 m above the sea level (a.s.l.) Temperatures vary from 23°C in lower altitudes (less than 1000 m) to about 15°C at 2000 m, with rainfall varying from 1000 to 2000 mm per year. Two types of climatic conditions exist in this region as determined by temperature variations and precipitation. The tropical Afro-mountain climate is found in the highlands and the Guineo-equatorial climate in the lowlands. Plains, plateaus, and chains of mountains give this area a great complexity of agro-ecological conditions. The soils range from kaolisols to ferralsols while others are alluvial soils or lithosols and xerokaolisols (Vyakuno, 2006). Agriculture in North Kivu is largely subsistence and employs over 80% of the working population mostly those from rural and poor regions, cultivating in marginal soils. It is practiced on mountain sides, steep slopes, ridges, plains, and in swamps. The fields are generally vulnerable to erosion, due to lack of control measures. Slash-and-burn with little or no fallow period is a dominant practice, causing tremendous decline in soils fertility thus, giving poor yields and increasing the pressure on natural forest reserves (Emilie *et al.*, 2015). Farmers use many ways to integrate trees into fields or pastures with diverse arrangements (on the edge, on contour lines, scattered, intercropped, corridors and alley crops), and they also apply improved fallows (Emilie *et al.*, 2015). Very often, they use taungya systems, as they intercrop annual crops during the first three years of tree plantation and then leave trees alone in fields up to five years before harvesting timber and then restart the cycle. Within farms, trees are planted in rows at a spacing varying from two to three meters according to the farmers' will. Moreover, they also diversify their agricultural practices by either growing perennial crops like coffee trees and cocoa under tree shades integrating within farms trees with high commercial value such as acacias; or practicing family gardens (Emilie and Subira, 2015). Study farms were selected randomly from four different locations near Butembo city. They are Lukanga, Musienene, Malende and Bunyuka (Figure 1).

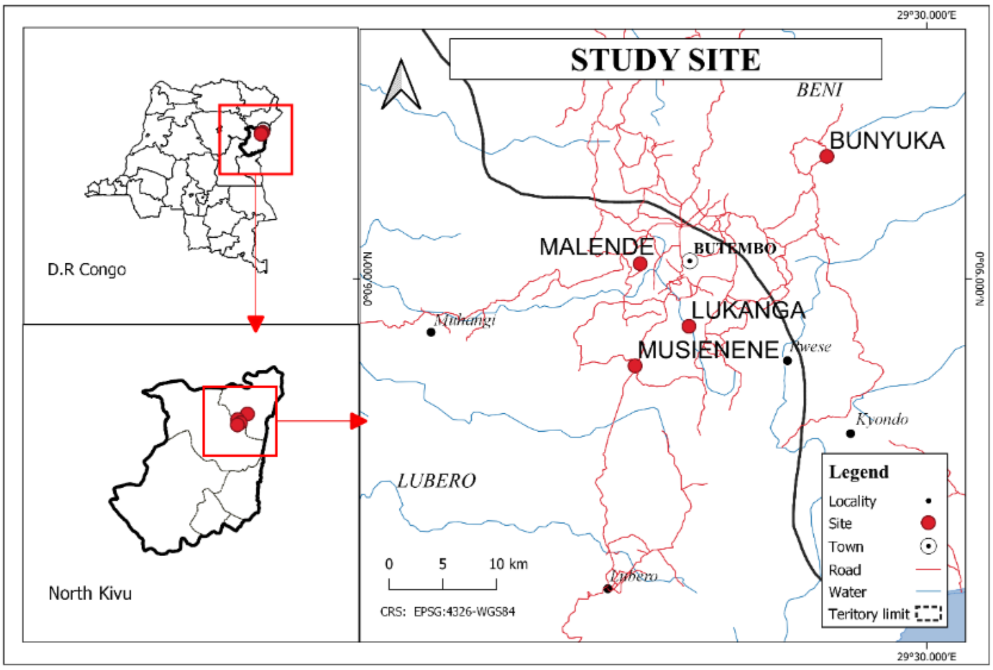

Figure 1. Study site map.

Table 1. Characterisation of the study site.

Sites	Altitude (m)	Annual rainfall (mm)	Temperature (°C)	Soil type	Soils characteristics
Bunyuka (Emilie *et al.*, 2015) (KASAY, 1998)	1873	1000-2000	23	Ferralsols (sandy clay loam) Alluvial soils	Deep and rich in humus; quite clayey and not very compact; without much reserve of organic matter on the surface.
Lukanga (Vyakuno, 2006)	1995	1330	18	Kaolisols (sandy clay loam) Ferralsols Lithosols	Slightly acidic; low in N, K and P; rich in Ca and hematite; brown to darkish colour; weak textural stability; erodible.
Malende (Sahani, 2011) (RDC, 2005b) (Sivirihauma, 2013)	1691	1365	22	Kaolisols (clay) Hydro-Xerokaolisols Ferralsols	High in clay content; humiferous; susceptible to collapses on slopes; brown to reddish colour.
Musienene (Vyakuno, 2006)	1759	1655.2	20	Kaolisols (sandy clay loam) Ferralsols Lithosols	Acidic; low in exchangeable bases and especially in Ca; strong textural stability; resistant to erosion.

Experimental design and treatments

The experimental layout was a complete randomized design. Five different treatments representing five different land cover were taken into consideration for samplings, namely *Eucalyptus saligna* and *Grevillea robusta* tree species in addition to three control farms: one negative control consisting of a piece of agricultural land with beans as cropped plant and with no tree species influence, and two positive controls, one set as a natural forest (constituted with 10 main species: *Syzigium guineense, Macaranga neomildbraediana, Bridelia ferruginea, Rapanea melanophloeus, Bellucia axinanthera, Piptadeniastrum africanum, Sephonia globeliflolia, Musanga cecropioides, Miriantus arboreus* and *Polisia vulvae*) and another one cropped with an indigenous tree species, *Ficus benghalensis*. At each location, five farms for each treatment were identified for sample collection. The different tree species represented the controlled factors and each farm within a site represented the replications. *Eucalyptus saligna* and *Grevillea robusta* were selected for this study because they are the most grown trees in the study region.

Criteria for selecting experimental sites

The criteria for selecting the farms were: (1) The size of farms: any selected farm had a minimum area of 0.5 ha, given that 0.5 ha is the common size of woodlots owned by farmers in the study region; (2) The tree attributes: all trees within the different farm replicates had comparable characteristics in terms of shape, height, and age of their plantation; (3) The dominance: samples were collected only in farms having woodlots of the tree species of interest only.

Collection of macrofauna

A soil monolith measuring 0.25 x 0.25 x 0.30 m was dug out in accordance with the Tropical Soil Biology and Fertility Program method (Anderson and Ingram, 1993). In each plot, following the method used by Mboukou-Kimbatsa and Bernhard-Reversat (2001), two randomly chosen transects forming a right angle were selected. In each transect, three monoliths (5 m distant from each other) were excavated making a total of six monoliths per plot. After the excavation, the soil was placed in containers for easy hand catching of soil macrofauna visible with naked eyes. During the hand catching, all soil macrofauna recovered were first conserved in 75% ethanol before being separated at the completion of the collection activity. These organisms were identified and grouped according to their respective taxonomy.

For the litter feeder macrofauna, pitfall traps and Winkler litter extraction methods were applied. Following the method used by Catherine and Steven (2001), five pitfall traps were set and implanted into the ground to the soil surface level along a randomly chosen transect at a 5 m interval. Pitfall traps were made of a plastic cup with dimensions of 9 cm in depth and 5.5 cm in diameter and partially filled with ethanol and remained on farms for seven days.

In the same transect, leaf litter was collected at 5 different sampling points using a quadrat of 0.25 m^2 for obtaining Winkler samples (Michael *et al.*, 2017). The whole 0.25 m^2 leaf litter was put in a bag sieve and sifted via a 10 mm mesh by vigorously shaking the bag sifter for nearly one minute. After sieving, the obtained samples were moved into Winkler bags and were suspended for 3 days for macrofauna collection (Hopp *et al.*, 2011).

Macrofauna abundance was determined as the number of individuals within every single field, while macrofauna diversity was estimated using the Shannon diversity index given as follow (Yeates and Bongers, 1999b):

$$H' = -\sum_{i=1}^{k} pi \log(pi)$$

Where pi is the proportion in groups k.

The Richness index was given as:

$$SR = \frac{S-1}{\log_e N}$$

Where S is the number of taxa identified in a sample and N is the number of all individuals identified in a sample.

The Evenness index was given as:

$$J' = \frac{H'}{H'max}$$

Where $H'max = \log_e S$

Table 2. Description of woodlots.

	Tree Fields sampled				
Tree species	*Eucalyptus saligna*	*Grevilea robusta*	*Ficus benghalensis*	Natural forest	Beans
Description	Farm purely cropped with *Eucalyptus saligna*	Farm purely cropped with *Grevilea robusta*	Indigenous species (Ficus) within farms	No agricultural activities	No trees. Beans based system

Macrofauna population was separated, at the order level, into seven different dominant groups (*Areneae*, *Coleoptera*, *Haplotaxida*, *Hymenoptera*, *Isoptera*, *Orthoptera*, and *Spirostreptida*). However, fifteen other macrofauna orders that were observed in very low numbers within farm units were combined to form one group that was named "Others". Those soil macrofauna groups are *Blatodea*, *Dermaptera*, *Diptera*, *Gastropoda*, *Hermiptera*, *Isopoda*, *Lepidopetra*, *Opisthopora*, *Opoliones*, *Phalangida*, *Polydesmida*, *Pseudoscorpionida*, *Scolopendrida*, *Solfugida*, *Stylommoptophora*.

Soil sampling for nutrients analysis

Subsequently the handpicking of the soil macrofauna, a composite sample of around 500 g was drawn from each farm for analysis. Soil parameters were total N and C, C fractionation, soil pH, available P, and exchangeable bases (Ca, Mg and K). Total C was determined using the Walkley-Black method (Nelson and Sommers, 1996), while the total N was determined by the Kjeldahl method (Bremner, 1965). For the P and the exchangeable bases (Ca, K and Mg), the Mehlich-3 procedure was used for their extraction (Mehlich, 1984).

Litter collection and characterisation

For the collection and analysis of leaf litter, Ukonmaanaho *et al.*, (2016) procedure was applied. Litter traps were installed under trees within each selected field for two weeks. The samples were then dried at room temperature and bulked before being carried to the laboratory for an oven drying at 60°C to a constant weight, after then milled in a ball mill and sieved using a 2 mm sieve. Litter characterization consisted of the determination of lignin and polyphenol content, total nitrogen and carbon, potassium, phosphorus, calcium and magnesium. Lignin was evaluated by the acid detergent fiber method, and polyphenols were determined by the Folin-Denis method (Anderson and Ingram, 1993). Total C and N were studied through the CN-analyser whereas P, K, Ca, and Mg were assessed via inductively coupled plasma atomic emission spectroscopy (Isaac and Johnson, 1998). It is important to note that litter or crop residue were not collected within bean farms for this study due to the fact that the litter collection method used was not appropriate for bean crop residue collection. Therefore, bean crop was not considered for litter analysis.

Statistical analysis

The analysis of variance (ANOVA) and correlation analysis were carried out using R programing software (R Core Team, 2015), and the Tukey's post-hoc comparisons (HSD tests) were executed at $\alpha = 0.05$ at each time the analysis of the variance (ANOVA) revealed significant effects. Tree species were considered as fixed factor whereas the replicates were considered as random factor. During correlation analysis, soil macrofauna abundance and diversity were entered as dependent variables while soil chemical properties were used as explanatory variables. The effects of the tree species and sites were tested using the generalised linear mixed models (GLMM) through the R package lme4 due to the fact that it was observed a nonconformity from normality (Shapiro-Wilk test), and an absence of homogeneity of variance (Levene's test) during the manipulation of the soil macrofauna data (Bates *et al.*, 2015). This was used to test the effect of tree species on soil macrofauna abundance and diversity, litter and soil chemical properties. The generalised linear mixed model was completed by using the negative binomial regression as an extension of the Poisson distribution due to the fact that the data had a lot of zero values (Bates *et al.*, 2015).

RESULTS

Chemical characteristics of litter

The quality of tree litter differed significantly based on the different species (Table 3). Total C content was significantly higher in litter under ficus (313.3 g kg^{-1}) and eucalyptus trees (293.4 g kg^{-1}) and lowest in grevillea (248.1 g kg^{-1}). On the contrary, N was higher in litter obtained from the natural forest (11.5 g kg^{-1}) compared to litter obtained in eucalyptus, ficus, and grevillea which had values below 10.0 g kg^{-1}. Exchangeable Ca and Mg were highest in ficus (3.3 g and 2.6 g kg^{-1}, respectively) while K was highest in litter obtained from natural forests. Differences in litter P content between the tree species were not significant. The lignin content of the litter collected from ficus and grevillea was significantly lower than the ones recorded in the natural forests and eucalyptus.

Soil chemical properties as influenced by tree species

Tree species identity significantly affected soil chemical properties as presented in Table 4. Soil pH was lower in soil under natural forest (4.8) compared to eucalyptus, grevillea, ficus trees as well as bean fields. Total C content was significantly lower in bean fields and gradually increased in grevillea, ficus, and eucalyptus, with the highest values in natural forests (60.7 g kg^{-1}). The mean values of total N were lower in soils under beans than in ficus and eucalyptus, while higher content was recorded under natural forest and grevillea (5.25 and 5.31 g kg^{-1} respectively). The soil exchangeable Ca was significantly higher in soil under ficus (3.16 g kg^{-1}) compared to bean fields, while soil under grevillea, eucalyptus and natural forest had values below 1.0 g kg^{-1}. Similar differences were observed for K and Mg.

Table 3. Litter chemical characteristics as influenced by tree species (mean ± (SE)).

Litter properties	Eucalyptus	Ficus	Grevillea	Natural Forest
C (g/kg)	293.4 ^{a} (19.0)	313.3 ^{a} (24.5)	248.1 ^{b} (15.1)	281.5 ^{ab} (16.8)
N (g/kg)	8.6 ^{b} (0.7)	8.4 ^{b} (1.1)	8.7 ^{b} (1.2)	11.5 ^{a} (2.5)
C/N ratio	35.0 ^{ab} (2.9)	42.8 ^{a} (10.1)	32.7 ^{ab} (6.7)	29.5 ^{b} (5.4)
P (g/kg)	2.5 (0.3)	2.8 (0.3)	2.3 (0.3)	2.9 (0.6)
Mg (g/kg)	1.5 ^{b} (0.4)	2.6 ^{a} (0.2)	0.9 ^{c} (0.2)	1.3 ^{bc} (0.4)
K (g/kg)	2.7 ^{b} (0.5)	3.0 ^{ab} (0.6)	2.4 ^{b} (0.3)	3.6 ^{a} (0.2)
Ca (g/kg)	2.1 ^{b} (0.5)	3.3 ^{a} (0.4)	2.8 ^{ab} (0.6)	0.6 ^{c} (0.1)
Polyphenol (%)	8.2 (1.7)	8.1 (1.6)	6.6 (1.0)	7.2 (0.8)
Lignin (%)	42.8 ^{a} (3.7)	25.9 ^{b} (2.5)	26.9 ^{b} (6.2)	39.0 ^{a} (3.4)
Lignin/Polyphenol	8.0 ^{a} (5.1)	4.1 ^{ab} (1.1)	5.9 ^{a} (3.7)	5.7 ^{ab} (0.7)

Within rows, means followed by different letters are significantly different at $p < 0.05$. Abbreviations: C=carbon, N=nitrogen, K=potassium, P=phosphorus, Mg=magnesium, Ca=calcium. Mean separation by Tukey's HSD test.

Table 4. Soil chemical properties as influenced by tree species (mean ± (SE)).

Soil properties	beans	Eucalyptus	Ficus	Grevillea	Natural Forest
pH	5.95 ^{a} (0.1)	5.6 ^{a} (0.3)	5.9 ^{a} (0.2)	5.5 ^{a} (0.4)	4.8 ^{b} (0.1)
C (g/kg)	33.6 ^{c} (3.6)	47.7 ^{b} (6.5)	46.2 ^{b} (6.5)	45.0 ^{bc} (9.1)	60.7 ^{a} (3.4)
N (g/kg)	3.7 ^{b} (0.2)	4.7 ^{ab} (0.7)	4.3 ^{ab} (0.4)	5.3 ^{a} (1.4)	5.3 ^{a} (0.4)
C/N ratio	9.0 ^{b} (1.1)	10. 5 ^{ab} (1.0)	11 ^{ab} (1.3)	10.0 ^{ab} (2.1)	11.8 ^{a} (0.4)
P (g/kg)	0.1 ^{a} (0.0)	0.03 ^{b} (0.0)	0.1 ^{a} (0.0)	0.03 ^{b} (0.0)	0.02 ^{b} (0.0)
Ca (g/kg)	1.8 ^{b} (0.4)	0.4 ^{d} (0.1)	3.2 ^{a} (0.3)	0.9 ^{c} (0.3)	0.6 ^{cd} (0.1)
Mg (mg/kg)	245.4 ^{b} (100.4)	16.4 ^{c} (5.8)	640.2 ^{a} (182.5)	238.4 ^{b} (82.8)	32.4 ^{c} (3.9)
K (mg/kg)	130.7 ^{b} (15.9)	80.7 ^{d} (11.8)	211.6 ^{a} (9.6)	117.4 ^{bc} (15.0)	97.5 ^{cd} (6.7)

Within rows, means followed by different letters are significantly different at $p < 0.05$. Abbreviations: C=carbon, N=nitrogen, K=potassium, P=phosphorus, Mg=magnesium, Ca=calcium. Mean separation by Tukey's HSD test.

Influence of tree species on macrofauna abundance and diversity

A total of 617 individuals in 22 macrofauna orders were collected during the study. Three orders, namely the *Hymenoptera*, *Coleoptera,* and *Areneae*, had the greatest abundance with relative abundance of 21.1%, 18.5%, and 13.9% respectively. In general, the abundance of the recovered orders of macrofauna significantly differed between the tree species (Table 5). For instance, ficus had a higher average number of macrofauna (131 individuals) compared to natural forests, grevillea, and eucalyptus (96; 80.7 and 80.1 individuals respectively), while bean plots had the lowest values (46.5 individuals). The mean values of Araneae were higher in bean plots (7.3 individuals) compared to grevillea and eucalyptus (6.0 and 5.1 individuals respectively) and had more than two times the values recorded in ficus and natural forests. On their side, Coleoptera was significantly higher in grevillea, eucalyptus, and ficus (9.9; 7.8 and 7.5 individuals respectively) in comparison to bean plots which represented at least half the value of any other system. Haplotaxida and Hymenoptera both had significant highest values in soils under ficus (23.3 and 77 individuals respectively). However, they had the lowest values under natural forest for Haplotaxida with zero count, and under beans (11.8 individuals) for Hymenoptera. Isoptera was not present in bean plots but had in both eucalyptus and natural forests at least five times values significantly greater than the ones from grevillea or ficus (2.3 and 2.5 individuals respectively). In general, macrofauna Shannon's diversity index was differently influenced by the different tree species with ficus having the lowest values (1.3) as compared to natural forests, eucalyptus, and grevillea, while bean plots had significantly greater values (1.6). These trends were also observed for the evenness index, while the species richness was significantly higher in soils under natural forests and ficus and gradually decreased under grevillea and eucalyptus, with bean plots recording the lowest values.

Correlation of soil chemical parameters and macrofauna abundance and diversity

Except for the Coleoptera, all the other orders showed a significant correlation with soil chemical properties (pH, C, N, P, K, Ca, and Mg) as shown in Table 6. The Araneae, Isoptera, and Orthoptera abundance was negatively and significantly correlated with P, Mg, Ca, and K while Hymenoptera were positively and significantly influenced by total C, C/N ratio, Mg, K and Ca. Haplotoxida were positively correlated with soil pH, C/N ratio, P, Mg, K, and Ca, but negatively correlated with soil total N. While Spirostreptida was strongly and negatively associated with total N and C, they were however positively influenced by K. A positive and strong correlation between the overall macrofauna abundance and the total C, the C/N ratio, Mg, K and Ca was observed. Soil pH was significantly and positively correlated with the diversity and evenness indices but negatively associated with the richness index. Soil Mg, total C, and C/N ratio revealed a negative and significant correlation with both the diversity and the evenness indices, whereas the richness index was positively correlated with soil total C and C/N ratio.

DISCUSSION

Soil chemical characteristics from woodlots with different tree species

Tree species had no impact on soil pH. Only natural forests had a pH significantly lower in comparison to other tree species. Considering that the soils within our study region are known to be acidic (Vyakuno, 2006), the introduction of exotic trees such as eucalyptus and grevillea in the study region may have been responsible for changes observed in the acidity of the soil. In fact, these kind of fast growing trees have been recognised to help in regenerating degraded soils under the tropics, and thus influencing their fertility and biodiversity (Harrington and Ewel, 1997). Moreover, the shifting cultivation where farmers practice slash and burn for weed control and for preparing farms for trees and crops plantation might be another reason explaining the trends observed in pH values. It has been reported that the ash resultant from the burning of the biomass could account for high pH values in concerned soils in comparison to soils where slash and burn is not practiced (Islam and Weil, 1999). These findings corroborate with those of Islam and Weil (1999) who also found lower values for soil pH under natural forests than the ones under tree plantation as well as cultivated farms.

Table 5. Soil macrofauna abundance and diversity as influenced by tree species (mean ± (SE)).

Soil macrofauna orders	Beans	Eucalyptus	Ficus	Grevillea	Natural Forest
Araneae	7. 3 ^{a} (3.5)	5.1 ^{ab} (1.8)	2.8 ^{b} (0.9)	6 ^{ab} (1.6)	3.3 ^{b} (1.1)
Coleoptera	2.8 ^{b} (1.0)	7.8 ^{a} (1.8)	7.5 ^{a} (2.5)	9.9 ^{a} (3.8)	5.8 ^{ab} (1.3)
Haplotaxida	12.5 ^{ab} (3.2)	3.5 ^{bc} (3.0)	23.3 ^{a} (9.9)	13.8 ^{ab} (7.1)	0 ^{c} (0.0)
Hymenoptera	11.8 ^{c} (7.0)	40.2 ^{bc} (13.3)	77 ^{a} (23.6)	33.2 ^{bc} (9.3)	58.3 ^{ab} (18.5)
Isoptera	0 ^{b} (0.0)	12.7 ^{a} (8.2)	2.5 ^{b} (1.2)	2.3 ^{b} (1.9)	12.8 ^{a} (7.1)
Orthoptera	2.5 (0.8)	3.1 (1.6)	3 (2.1)	2.6 (1.0)	3.3 (0.5)
Spirostreptida	3.8 (2.7)	1.3 (0.6)	3.8 (1.9)	4.1 (5.9)	1 (0.3)
Others	6 ^{b} (1.7)	6.5 ^{b} (2.2)	11.5 ^{a} (3.1)	9 ^{ab} (2.8)	11.8 ^{a} (2.1)
Total abundance	46.5 ^{c} (2.3)	80.1 ^{b} (15.7)	131.3 ^{a} (21.4)	80.7 ^{b} (14.6)	96 ^{b} (202)
Diversity indices					
Shannon DI	1.6 ^{a} (0.2)	1.5 ^{ab} (0.2)	1. 3 ^{b} (0.2)	1.6 ^{ab} (0.1)	1.3 ^{ab} (1.0)
Richness	7.5 ^{b} (0.7)	8.8 ^{ab} (0.9)	9.5 ^{a} (0.5)	9 ^{ab} (0.7)	9.8 ^{a} (1.0)
Evenness	0.8 ^{a} (0.1)	0.7 ^{abc} (0.1)	0.6 ^{c} (0.1)	0.7 ^{ab} (0.0)	0.6 ^{bc} (0.1)

Within rows, means followed by different letters are significantly different at $p < 0.05$. Abbreviations: DI=diversity index. Mean separation by Tukey's HSD test.

Table 6. Pearson correlation coefficients between soil macrofauna abundance and diversity, and soil chemical parameters.

Macrofauna orders	Soil properties							
	pH	N	C	C/N	P	Mg	K	Ca
Araneae	0.04	0.18	0.03	-0.18	**-0.21***	**-0.19***	**-0.22***	**-0.31***
Coleoptera	-0.16	-0.08	-0.10	0.10	-0.13	-0.15	-0.03	-0.08
Haplotaxida	**0.26****	**-0.36*****	-0.18	**0.34*****	**0.4*****	**0.53*****	**0.56*****	**0.57*****
Hymenoptera	-0.16	0.02	**0.34*****	**0.31****	0.02	**0.38****	**0.33*****	**0.28****
Isoptera	-0.07	-0.02	0.09	0.14	**-0.22***	-0.18	**-0.26***	**-0.25***
Orthoptera	-0.04	0.06	-0.14	**-0.24***	-0.08	**-0.28****	**-0.27****	-0.17
Spirostreptida	-0.04	**-0.23***	**-0.26****	0.09	0.13	0.13	**0.20***	0.20
Others	-0.15	0.02	**0.21***	**0.31****	-0.07	0.19	**0.23***	0.13
Total abundance	-0.12	-0.13	**0.24***	**0.46*****	0.06	**0.46*****	**0.42*****	**0.37*****
Shannon DI	**0.21***	0.08	**-0.24***	**-0.28****	0.11	**-0.28****	-0.12	-0.11
Richness	**-0.20 ***	0.06	**0.24***	**0.28****	-0.15	0.10	0.12	0.00
Evenness	**0.27****	0.02	**-0.33*****	**-0.33*****	0.15	**-0.24***	-0.13	-0.09

Abbreviations: C=carbon, N=nitrogen, K=potassium, P=phosphorus, Mg=magnesium, Ca=calcium, DI=diversity index. Coefficients marked in bold indicate a significant correlation: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Low pH recorded in soil under natural forest might have induced the lower exchangeable K, Mg, and Ca observed under natural forest ecosystems. In fact, Bailey *et al.* (2005) suggested that soil acidification habitually induces the replacement of basic cations by Al^{3+} and H^{+} ions at the exchange pools such that it is observed a depletion of the soil base cations. On the other hand, the higher content of soil exchangeable K, Mg and Ca under ficus might be a result of lower content of its litter lignin. In fact, it has been acknowledged that litter with higher lignin decomposes slowly given that lignin has the ability to resist enzymatic attacks and to physically interfere with the release of other litter chemical elements (Dhanya *et al.*, 2013). Thus lower lignin has been linked to faster nutrient release and availability in soil due to higher rate of decomposition it induces. In addition, even though litter from natural forest had an improved C/N ratio, which could have meant better decomposition rate, however the lower lignin in ficus litter may have also promoted a quicker mineralisation, thus induced a higher Ca, Mg and K content in soil under ficus. In fact, despite that litter with lower C/N ratio is recognised to mineralize quicker, however Jama and Nair (1996) carried out an experiment comparing decomposition rates of a filter paper having higher C/N ratio and litter of some tree species with lower C/N ratio but with higher lignin and found that the filter paper had higher decomposition rates compared to trees litter, and suggested that a great C/N ratio might not have limiting influence when lignin is present in small quantities in litter.

The significant high values of OC recorded under natural forests can be explained by its huge plant diversity, which implies a much-diversified litter quality. It has been argued that variations in soil OC are, among other things, influenced by the quantity and quality of litter fall incorporated into the soil from trees and shrubs (Worku *et al.*, 2014). Leonardo *et al.* (2018) have indicated that tree diversity within a forest contributes to enhancing soil fertility. This is due to an improvement in soil organic matter content as a result of a diversified trees and stem litter fall biomass decomposition (Noella *et al.*, 2015). In addition, the absence of soil disturbance through soil tillage under natural forest might have induced higher organic C accumulation, contrarily to the other systems where tillage is applied during soil preparation for trees and crops plantation. In fact, it has been documented that, compared to soils under tillage, non-tillage soils (undisturbed soils) tend to accumulate more plant residues on the soil surface, thus additional organic matter, which increase soil organic C content (Angers and Eriksen-Hamel, 2008). Further, the absence of soil disturbance via zero or minimum tillage slows down the decomposition rate of organic matter, which indubitably plays a great role in increasing soil organic C content (Szostek *et al.*, 2022). In accordance with these findings, while testing the effect of conversion of natural forests into eucalyptus plantations in Brazil on soil properties, Cortez *et al.* (2014) found that soil total organic carbon (TOC) showed a reduction of organic carbon in the first year of the conversion. Also, Leda and Welington (2018) confirmed the same results as they found that soil organic carbon concentration diminished around 15% in the 10-25 cm soil stratum and 10% in the 35-50 cm stratum beneath eucalyptus farms after conversion of natural forests. Sharma (2011) found similar results with the lowest values of organic C recorded within arable/cultivated farms, which are almost homogeneous in terms of litter quality, in comparison to tree-based systems.

The lowest values of total N under beans against the highest values under grevillea can be described as a result of low organic input through crop residue restitution under bean farms. Added to this, the higher degree of nitrogen leaching from the soil due to low land cover in bean farms in comparison to the other tree based fields might have induced low N content under beans. In previous studies, results with the same trends have been highlighted where cultivated farms had lower N content in comparison to grevillea and natural forests (Islam and Weil, 1999). The higher P content under bean plots in this study might be due to the kind of vegetation in place within the plots which is characterised by the absence of tree species and the predominance of annual crops. This commensurate with Avendaño-Yáñez *et al.* (2018) who suggested that soil P content might be increased due to herbaceous vegetation in locations deprived of trees presence in comparison to those under tree canopies. Hence, agricultural crops-soil systems might likely be more crucial for P enrichment than that of trees-soil systems due to the fact that it has been demonstrated that permanent tree plantation biomass may lead to a long-standing immobilisation of P (Alemie, 2009; Aweto and Moleele, 2005).

Soil macrofauna abundance and diversity in different tree species woodlots

Soil macrofauna are influenced by trees, as a result of trees' organic input differentiation either qualitatively or quantitatively (Korboulewsky *et al.*, 2016). The particular trends of soil macrofauna abundance and diversity beneath different tree species for this study might have been impacted by the organic inputs, after litter decomposition as well as root turnover. For instance, natural forests did not record any individual of Haplotaxida order (earthworms). This situation can be elucidated by the fact that this order significantly and positively correlated with soil pH. This soil parameter has indeed been recognised to reduce soil biological activities and organisms' development (Castro-Díez *et al.*, 2011). Additionally, earthworms' abundance trends in this study can be attributed to the difference of P levels across all the treatments. In fact, higher abundance of Haplotaxida order was found in soil under ficus plots which also had the highest values for P. Besides, Haplotaxida order was strongly and positively linked with soil P. Previous researches revealed that earthworms are generally influenced by the amount of P in soils such that several authors have attributed the higher quantity of earthworms in soils under trees canopies to higher P content (Barrios *et al.*, 2005; Kamau *et al.*, 2017; Mbau *et al.*, 2015).

It was observed that the abundance of Araneae order (spiders) was greater under bean plots compared to any of the tree species. This might be linked to the nature of spiders' habits and preferences in regard to the suitable environment for their lifestyle. Previous studies have highlighted that agroecosystems receiving much light are favourable to spiders' development because higher herbaceous vegetation cover is promoted in presence of a greater luminosity reaching the farm, such that the amount of herbivores, essential spiders' prey, is increased (Boyle, 1999). In addition, high herbaceous vegetation coverage together with fallen trunks constitute a suitable booster and support for fixing the spiders' webs. Consequently, based on the distinctiveness of microhabitats and microclimate created by the amount of light perceived, forests and non-forests systems are differently constituted in terms of Araneae abundance (Peres *et al.*, 2014).

The lowest soil abundance of Coleoptera (beetles), Hymenoptera (ants), and Isoptera (termites) recorded in soil under beans might be an indication of the higher level of disturbance within this agro ecosystem. In fact, Sheila *et al.* (2016) and Baretta *et al.* (2014) indicated that soil macrofauna is greatly influenced by the kind of management activities in place as they alter soil structure, such that they acknowledged that intensification in a given land use has negative effects on soil macrofauna populations. Added to this, lower Hymenoptera and Isoptera abundance under bean plots in this study corresponds to lower value of soil total N and soil C they also recorded. This might be associated with the feeding habits of these two macrofauna orders. Hymenoptera (ants) and Isoptera (termites) have been recognized to participate in soil N and soil C break down indirectly through the activation of soil microorganisms. In fact, soil microorganisms are not much dynamic such that they only have the potential to move nearby for micro distances (through the soils pores filled with water and with the roots growing movements) in order to look for substrates to feed on, yet they are acknowledged to have higher aptitudes to digest almost all the organic matter found around them. Due to the fact that termites and ants have the ability to move soil particles while feeding on soil substrate, and thus to transform the environmental settings at the scale of soil microorganisms, they therefore provide assimilable materials that boost the metabolic aptitudes of microorganisms, ending up enhancing soil N and soil C mineralisation (Ruiz *et al.*, 2008). On the other hand, Isoptera were more abundant in natural forest. This result coincides with the highest content of lignin observed in natural forest and eucalyptus and this trend might justify the higher presence of Isoptera they recorded. Besides, Isoptera are recognised to populate recalcitrant organic matter as they have the ability to digest low quality organic matter thanks to their aptitude to produce a great range of enzymes from the related gut microflora (Lavelle, 1997).

This study revealed a great species richness in soil under natural forests. This can be elucidated by the greater heterogeneity and amount of litter resulting from a greater tree diversity in natural forests. In fact, highly diversified litter incorporated into soil implies bigger supply of food as well as better microhabitats, improved soil conditions, and a healthier microclimate for macrofauna (Korboulewsky *et al.*, 2016). Leonardo *et al.* (2018) found the same trends in their study while comparing macrofauna species richness under natural forests to other tree-based systems. Likewise, Sheila *et al.* (2016) found that, compared to eucalyptus plantations, native forests had the uppermost group richness of soil macrofauna. However, in our work, the high proportion of the Hymenoptera and Haplotaxida orders under ficus affected evenness and Shannon's diversity indices in other orders, causing the ficus to reveal low values on these ecological indices. In agreement with this, similar outcomes were revealed by Leonardo *et al.* (2018) with a prevalence of Isoptera order in natural forest implicating an exhibition of low evenness and diversity indices values in natural forest in comparison to other agro ecosystems.

CONCLUSIONS

This study was conducted to assess the effect of diverse tree systems on soil macrofauna abundance and diversity and soil chemical properties (total N and C, soil pH, available P, Ca, Mg and K) for informed tree species selection and sustainable soil fertility management. It was shown that soil macrofauna reacted in different ways to diverse tree species. For instance, the Isoptera (termites) order was higher in natural forest, presumably due to higher lignin content therein recorded. Inversely, the Haplotaxida (earthworms) order was higher in cultivated trees and crops farms compared to natural forest. This has been linked to lower values of pH observed under natural forest. However, high soil disturbance under beans occurring during soil preparation in the region have triggered a reduction in Coleoptera (beetles), Hymenoptera (ants) and

Isoptera communities abundance. Natural forest induced higher species richness, consequential to its greater tree litter diversity. Nevertheless, soils under ficus recorded lower values for Shannon diversity and the evenness indices due to greater counts of Haplotaxida and Hymenoptera orders they recorded. It was observed that organic C and N were lower in soils beneath cultivated trees and crops farms, except for N under grevillea, but higher in soils under natural forest, indicative of greater tree species diversity under natural forest. This suggests that, the soil chemical characteristics were positively influenced in soil under natural forest unlike in soil under tree cultivation that had detrimental impacts on them. The diversified litter from natural forest proved to induce soils under natural forest to have higher soil macrofauna abundance and diversity. Thus, it is advisable to consider a great diversification of tree species while integrating trees within crop farms for maintaining better soil biodiversity and soil fertility management.

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