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Comparative Analysis of the Impacts of Commercial Exotic Forestry on Soil Fertility In the Southern Highlands of Tanzania: A Study of Pine, Eucalyptus and Black Wattle Plantations

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abstract

Pine, eucalyptus and black wattle trees have been planted worldwide for commercial forestry and carbon sequester. These species affect soil fertility differently depending on climate and ecosystem. In the southern highlands of Tanzania, these trees replaced most of the native forests, grasslands and cropland, but their impacts on soil fertility are uncertain. The study compared *Pinus patula*, *Eucalyptus grandis* and *Acacia meansii* (black wattle) forest soils to surrounding natural forests, grasslands and cropland. 18 study sites were selected based on the related location and land use. Each site had two transects; each transect had three 25 m x 20 m rectangular plots for soil sampling. Soil pH, macro and micro-nutrients were measured to determine the soil fertility. The results show that pine, eucalyptus and wattle trees had significantly lower soil organic carbon than cropland and natural forests ($p<0.05$). The pine and wattle forests had lower pH than the surrounding cropland and natural forests ($p<0.05$). Farmlands and natural forests had significantly higher mean soil total nitrogen than the pine, eucalyptus and wattle forests ($p<0.05$). However, the wattle forests had a higher mean TN (1.16%) than the pine and eucalyptus forests (0.13%). Liming and application of phosphate-based fertilisers are recommended when farmers use the harvested exotic tree farms for food crop production.

Introduction

Exotic trees such as pines (*Pinus patula*), eucalyptus (*Eucalyptus grandis*) and black wattle (*Acacia mearnsii*) have been widely planted around the world, even in non-native areas, for many decades. The purpose of planting these trees is to meet the global demand for timber, restore degraded ecosystems and sequester carbon as a nature-based solution to combat climate change. This also helps to reduce the pressure on natural forests for firewood and charcoal (Costa et al., 2022). These trees are currently found in many forests and savannah ecosystems, including tropical countries like Tanzania (Archibald et al., 2019; Heringer et al., 2019).

Pine, eucalyptus and black wattle plantations are known to enhance soil fertility by adding organic matter and retaining soil moisture (Woś et al., 2022; Mengistu et al., 2022; Lewis and Hossain, 2022). The eucalyptus trees can grow well in nutrient-poor soils and improve soil fertility by taking up nutrients from deeper soil the layers and adding soil organic matter from litter decomposition as reported by Souza et al. (2020). On the other hand, wattle trees are beneficial to the soil fertility due to their ability to fix nitrogen, which is essential for soil health as discovered by Rocha et al. (2020).

Although exotic tree plantations offer several advantages, some studies have revealed their adverse impacts. They are reported to disrupt the soil nutrient cycling, diminish water quality and quantity and cause habitat loss for flora and fauna (Council, 2000; Sharma et al., 2019; Perdomo-González et al., 2023). These trees also contain high levels of allelochemicals that can inhibit a growth of native plants such as shrubs, herbs and grass, hence reducing soil microbial activity and depleting soil nutrients (Mugayi, 2019; Nair et al., 2021; Pairo et al., 2021; Xu et al., 2023).

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Pine and eucalyptus trees are known to remove significant amounts of nutrients such as nitrogen and phosphorus from the soil, which can negatively affect the soil fertility (Osiecka et al., 2020; Yin et al., 2021; Castro-Díez et al., 2021). However, the wattle trees can also outcompete native species, leading to the reduced diversity and productivity of the ecosystem as observed by Jansen and Kumschick (2022). In these cases, the impacts of exotic tree plantations vary depending on a type of exotic species, nature of the soil, climatic conditions and whether they replace native vegetation or are planted in a bare land.

In the southern highlands of Tanzania, about 250,000 hectares of land are dedicated to exotic tree plantations. Njombe Region is leading, with around 89,843 hectares of exotic tree plantations (Arvola et al., 2019) planted in virgin grasslands and some in nutrient-exhausted farms and to a lesser extent in small unprotected natural forests. Pines (*Pinus patula*), eucalyptus (*Eucalyptus grandis)* and black wattle (*Acacia mearnsii*) are major exotic trees grown in Njombe Region. They were previously imported from Australia, North and Central America and then adopted by individual farmers in 1990s (Ngaga, 2011). According to Arvola et al. (2019), 70% of the exotic tree plantations in Njombe Region are owned by individual farmers 17% by the government and 10% by the private companies such as Tanganyika Wattle Company (TANWAT) and Participatory Plantation Forestry Programme (PFP) to mention a few. The government emphasised exotic tree plantations for poverty alleviation and protection of natural forests from overexploitation for firewood collection, charcoal making, timber and climate regulation.

However, the expansion of exotic tree plantations in the southern highlands of Tanzania has raised concerns about preserving the natural environment and its associated ecological systems. Although a few studies have shown the economic value of the exotic plantations (Lusasi et al., 2019; Mhando et al., 2022) and their effects on edible orchids and grassland amphibians (Ndaki et al., 2021; Lawson et al., 2023) in the study region, limited knowledge exists regarding their impacts on soil fertility in Njombe Region.

Since exotic tree plantations do not provide annual income to the rural communities, most tree farmers reuse some of the harvested exotic tree farms for food crop production, such as cereals, fruits like avocadoes as well as round potatoes that provide annual income for their economic development.

Hence, it was essential to understand the status of soil chemical properties under exotic plantations to make informed decisions on management practices, including types of fertilisers to apply. Therefore, this study aimed to investigate the impacts of exotic pine, eucalyptus and black wattle plantations on soil chemical properties compared with the natural grasslands, natural forests and farmlands in the southern highlands of Tanzania, where large land areas have been planted. The results of this study have significant implications for implementing sustainable land management practices and conserving biodiversity in the study region. They provide valuable insights to guide future decisions regarding forestry practices, crop production, conservation strategies and the overall ecological balance of the study area.

Materials and Methods

Description of the Study Area

This study was conducted in Njombe Region, which lies between latitudes 08° 50' and 10° 30' and longitudes 3° 3.45' and 35° 45' south of the equator (Figure 1). Njombe is one of the three regions comprising Tanzania's southern highlands. The region is situated between 1000 and 3,000 metres above sea level. The region experiences short-dry and long rainfall seasons. Significant seasonal variations in the annual total rainfall range from 600 mm to 1,600 mm (URT, 2018).

There are three distinct climatic and agroecological zones in Njombe Region, namely lowland, midland and highland. This study was conducted in the highland zone, which is known for its heavy rainfall with an annual mean precipitation range of 1,000 mm to 1,600 mm falling in a single season from November to May, followed by a dry and cold season from May to October. Its temperatures vary from 0°C in May and June to between 20°C and 24°C in October and November. The highland zone is mountainous with plains and it includes the majority of Makete District, western portions of Ludewa as well as the central and eastern portions of Njombe and Wanging'ombe Districts. The study area has reddish-yellow, highly weathered, well-drained and leached clay soils ideal for growing maize, beans, peas, tea, wheat, sweet and Irish potatoes, temperate fruits like avocados and apples as well as coniferous trees such as pines, eucalyptus and black wattle. The study zone is characterised by shrublands, unique plateau grasslands and evergreen Afromontane forests.

Njombe is the leading region in Tanzania in exotic tree production. The choice of the study area was based on the ongoing exotic tree plantation practices in many parts of the region conducted by rural communities, private companies and the government. The study was conducted in eight wards based on the presence of the selected exotic plantations (eucalyptus, pines and black wattle) and the natural forests, grasslands and farmland adjacent or near to exotic tree plantations (Figure 1).

Criteria for Selection of Sampling Sites

The sampling sites were chosen based on the Ecological Land Type Phase (ELTP). ELTP helps in identifying, mapping and classifying variables such as dominant vegetation, slope, elevation, soil type and the aspect of an area (Van Kley et al., 1995; Shao et al., 2004). The study area was dominated by common native indicator plants like *Bidden pilosa* and fens. Also, it had an abundance of exotic trees such as *Pinus patula*, *Eucalyptus sp* and *Acacia meansii*. To ensure that the sampling sites had similar soil characteristics, the Natural Resource Conservation Service (NRCS) soil survey map was used to identify the soil type. According to the NRCS soil survey map, numerous soil-specific groups exist within a certain ecological land type. However, most of these groups have similar characteristics and only slightly vary among them. The study area had well-drained acrisol soils, which are commonly found in regions with high rainfall. These soils are characterised by extensive leaching, low nutrient levels, excess aluminium and high acidity (Sanchez et al., 2009). The study sites were dominated by clay and sandy-clay soils, with pH levels ranging from 3.32 to 4.86. The sampling sites were located on flat and gentle slopes at elevations ranging from 1842 to 2170 m.

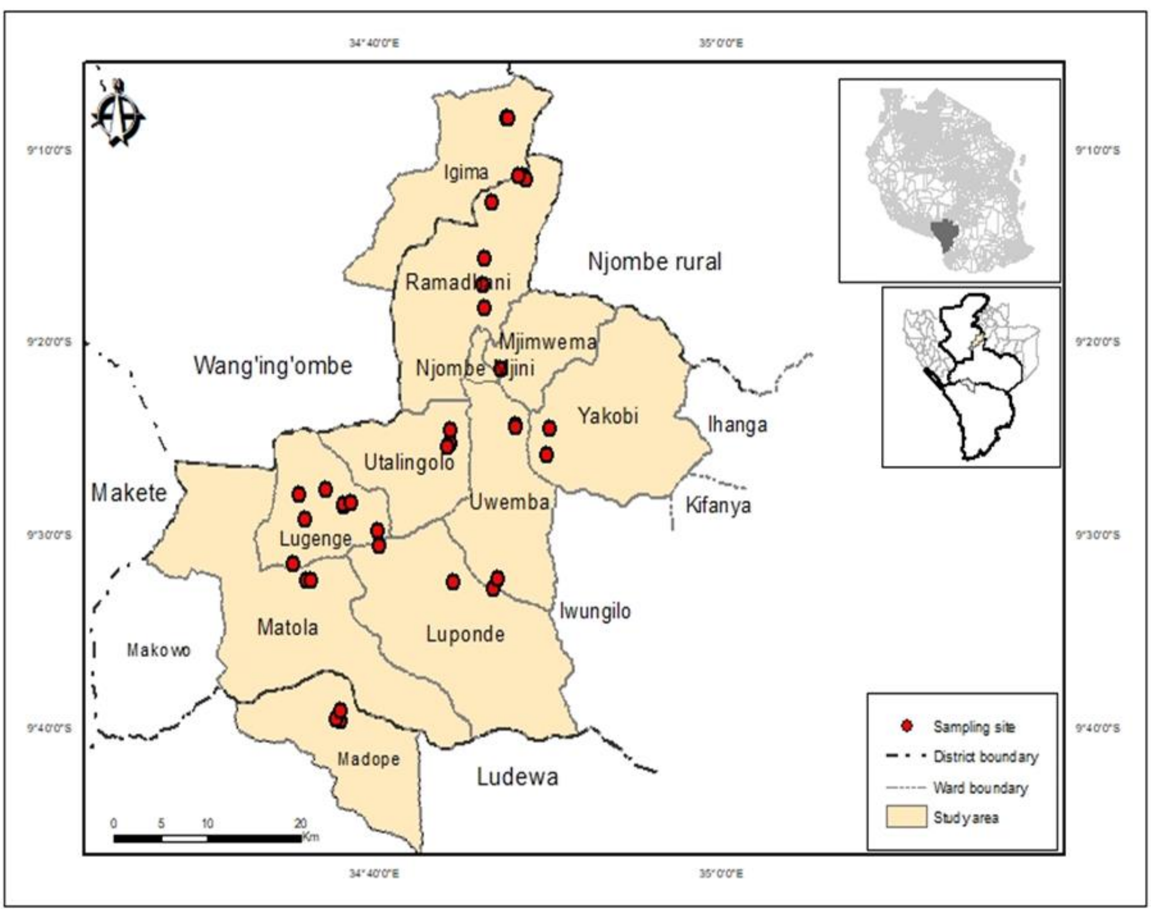

Figure 1: Location of study areas
Source. Cartographic unit, university of Dar es Salaam

Tree Planting and Management Practices

The government and the rural communities used traditional tree-planting methods, while the private companies used modern techniques. Farmers estimated planting space, ranging from 2.5 m to 3.0 m and planted trees without clearing the vegetation. Neither fertiliser application nor weeding was done, but pruning was conducted in the fifth and eighth years after planting; then, trees were left to mature. However, the private companies cleared vegetation, applied fertilisers, herbicides and pruning. The study focused on rural communities' tree farms, which own 70% of the plantations. It was conducted in tree farms owned by individual farmers which were planted in virgin grasslands and had not been harvested since the first rotation.

Soil Sampling and Laboratory Analysis

A soil survey was conducted to identify sampling sites. The researchers ensured that the sampling area included six chosen land use types–pine forests, eucalyptus forests, black wattle forests, natural forests, grasslands and farmlands–located adjacent or near to each other. The natural forests and grasslands were used as control sites, while the soil in farmlands was examined to compare its properties with the other land uses as farmlands are subject to human activities such as application of fertilisers that can alter their chemical properties. The sampling sites were randomly selected from three sampling sites for each land use, making up 18 sampling sites. From each sampling site, two transects were set, which were 95 metres long and 75 metres apart. After every 10 metres along the transects, three rectangular plots were established measuring 25 by 20 metres, alternating with one another to make a total of 108 soil sampling plots. The transect intervals were chosen to match the size of land uses, as most exotic trees are planted in plots of approximately half to ten hectares. The tree species were specifically studied because they are preferred by farmers and grow faster than the native trees.

The study prioritised the older plantations, which were more than 20 years old, to compare soil nutrients with those of the natural forests, grasslands and farmlands (Quiroz et al., 2021). Soil samples were collected using a soil auger at a depth of 0-40 cm, where most plant roots exist for nutrient uptake. Samples were collected, one from the centre and four from each corner of each plot (Katsumi et al., 2021). The soil samples from each plot were mixed separately to create a composite of that particular plot. Around 500 g of each composite was packed in polythene bags, labelled and sealed properly to avoid contamination. The composite samples were sent to the soil laboratory at Sokoine University of Agriculture (SUA) for chemical analysis. In the lab, the soil composites were air-dried, pulverised and sieved through a 2-mm sieve to make some powder. They were then analysed using standard methods as indicated in Table 1 below.

5 Data Analysis

The one-way analysis of variance (ANOVA) was used to compare the means of soil nutrient parameters of each exotic forest (pine, eucalyptus and black wattle) with those of the natural forests, grasslands and farmland. Graphs were plotted in a Microsoft Excel spreadsheet.

Results and Discussion

Concentration of Soil Nutrients among the Selected Land Uses

The study aimed to determine if there were any differences in soil parameters across the various study land uses such as pine, eucalyptus, black wattle, farmland, grasslands and natural forests. The ANOVA results indicated that soil characteristics do differ significantly across these land uses. Since Levene's statistics were significant, an equal variance could not be assumed. Hence, the Post Hoc was used to assess the differences in soil characteristics among the land uses using Dunnett's T3. The findings revealed that the exotic tree plantations significantly alter the chemical characteristics of the soil, both positively and negatively.

Soil pH

The study found that the average soil pH in the pine and black wattle plantations was significantly lower (3.94 ± 0.42 and 3.89 ± 0.1 respectively) than that in the farmlands (4.90 ± 0.36) and the natural forest (4.57 ± 0.42) ($P < 0.05$). However, the pH in the grasslands (4.02 ± 0.31) was not significantly different from that in the pine and black wattle plantations. On the other hand, the average soil pH in eucalyptus plantations (4.36 ± 0.54) was significantly lower than that in the farmlands, but significantly higher than in the grasslands ($P < 0.05$). There was no a significant difference in pH between eucalyptus plantations and natural forests (Figure 2a).

Despite the differences, the overall pH was below the critical range of 5.5-7.5 for normal plant growth as described by Landon (1991) as well as Motsara and Roy (2008). When compared to the pH of other land uses, the pH of the exotic tree plantations was significantly lower, similar to the findings by Singwane and Malinga (2012), Hong et al. (2018) and Yin et al. (2021), who reported that the soil acidity increased as a result of the invasion of black wattle and plantation of pines and eucalyptus.

The low pH below the critical range of 5.5 may have a detrimental effect on microbial activity and may result in a deficiency of some soil nutrients (Bojórquez-Quintal et al., 2017). The pH of the soil was measured since it is an important component that affects chemical reactions by regulating the solubility of nutrients in the soil. In the pH range of 6-7.5, soil nutrients become available for plant absorption. Lowering the pH below 5.5 inhibits microbial activities and increases the solubility of Al, Mn and Fe, all of which are harmful to plants in excess (Bojórquez-Quintal et al., 2017). Low pH could have been caused by high rainfall in the study region (Kim et al. 2022). The region experiences short dry and long rainfall seasons; the annual rainfall ranges from 600 mm to 1600 mm (URT, 2018). High rainfall leaches the alkaline elements such as Ca, Mg and K from the soil, leaving acidic elements like H^+ and Al (Neina, 2019; Kim et al., 2022).

However, the soil acidity in pine as well as eucalyptus forests and grasslands was significantly lower than that of the farmlands, similar to the findings by Singwane and Malinga (2012) in Swaziland and Liang et al. (2016) in Ethiopia, who all found low soil pH in the pine and eucalyptus forests compared to the nearby natural forests and farmlands respectively. This could be due to the low organic matter in those soils. The decomposition of organic matter by microorganisms releases carbon dioxide (CO_2), which forms weak carbonic acid when combined with rainwater and increases the acidity of the soil (Kim et al., 2022).

Table 1: Standard Methods for Soil Nutrient Analysis

Soil Nutrient/Parameter	Methods of Measurement	References
Soil pH	Potentiometric method in a ratio of 2.5:1 soil water suspension	Jones (2018)
Total nitrogen (TN)	Micro-Kjedahl digestion-distillation method	(Piper, C. S. 2019)
Soil organic carbon (SOC)	Walkey-Black method	Nelson (1982; Piper, 2019)
Extractable phosphorus (P)	Olsen method	(Bray and Kurtz 1945; Okalebo et al. 2002)
Exchangeable bases calcium (Ca^+), magnesium (Mg^+) potassium (K^+)	Ammonium acetate saturation method. Flame photometry determined (K^+) and atomic absorption spectrophotometry determined (Ca^+ and Mg^+).	(Chapman 1965; Okalebo et al. 2002; Piper, C. S. 2019)
Micronutrients copper (Cu), zinc (Zn), manganese (Mn) and iron (Fe).	Diethylenetriaminepentaacetic acid (DTPA) method	(Lindsay and Norvel 1978; Jones 2018; Piper 2019)

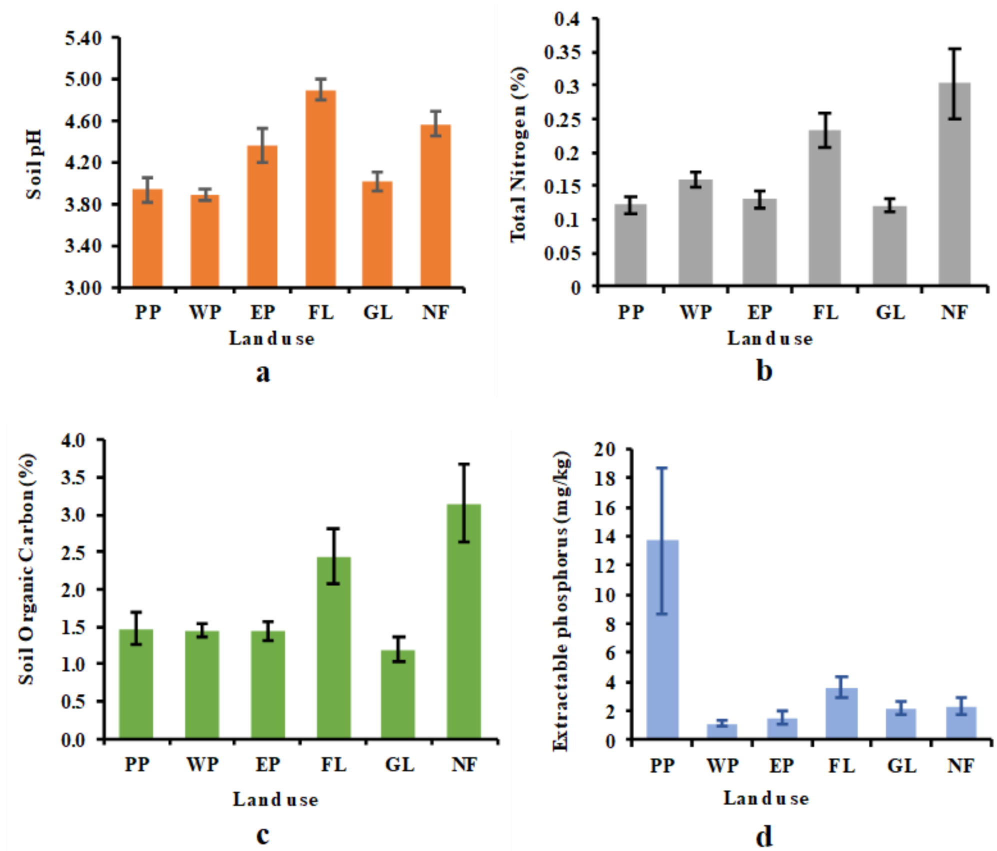

Figure 2: Comparison of the mean soil pH, TN, Ext P and SOC in the selected land uses
(PP = Pine plantations, WP = wattle plantations, EP = eucalyptus plantation, FL = farmland, GL = grasslands, NF = Natural forests)
Source: Field data 2021

Total Nitrogen (TN)

Figure 2b represents the mean percentage of total nitrogen concentrations in the selected land uses. The mean percentage of the total nitrogen (TN) content of soils under the pine plantations was 0.12 ± 0.05, whereas that of eucalyptus plantation soils was 0.13 ± 0.05 and of black wattle plantation soils was 0.16 ± 0.04. The mean percentage of TN values for natural forests was 0.30 ± 0.19, whereas for grasslands and farmlands were 0.12 ± 0.03 and 0.23 ± 0.09 respectively. Both Landon (1991) and Motsara and Roy (2008) defined the total nitrogen content of the soil as follows: 0.13% was considered to be low, 0.13% to 0.23% was considered to be medium, 0.23% to 0.30% was considered to be high and >0.30% was considered to be extremely high. According to this classification, the soils in the study area had an average concentration of TN ranging from extremely low to very high. A high mean concentration of TN was found in both natural forest and farmland soils, with the former having a value of 0.3% and the latter a value of 0.23%. Black wattle, eucalyptus and pine plantations had medium amounts of soil total nitrogen consistent with what was found for organic carbon in these types of land uses in the present study. There was no a significant difference between the mean nitrogen of grasslands and that of pine and eucalyptus plantations ($p<0.05$). However, the mean nitrogen content of the farmlands and natural forests was significantly greater ($p > 0.05$) than that of pine, eucalyptus and wattle forests. However, there was a statistically significant difference between the TN levels in the grasslands and those in black wattle plantations ($p < 0.05$). Despite this difference, black wattle plantations had higher nitrogen concentrations than pine and eucalyptus plantations.

The farmlands and natural forests had significant concentrations of TN, which is concurring with the findings by Li et al. (2019), Mugayi (2019) and Zhang et al. (2020). The high quantities of organic carbon found in natural forest and farmland soils were most likely to be a result of the decomposition of the organic matter and the use of nitrogenous fertilisers in agriculture, which contributed to the high nitrogen concentrations in such soils. According to Zhang et al. (2020), the moderate amounts of nitrogen found in exotic tree plantations may be consistent with the moderate levels of the organic carbon and NO3-nitrogen leaching from heavy precipitation. Grasslands showed low soil TN (0.12%), which may be because of the low levels of organic carbon detected (Lebenya et al., 2018).After comparing the TN in the soils of pine and eucalyptus plantations, it was found that the soils of black wattle plantations had a greater mean nitrogen content. Black wattle trees are among the woody nitrogen-fixing trees and are also a member of the legume family (Fabaceae); thus, contributing to an increase in the amount of nitrogen in the soil (Rocha et al. 2020); Nair et al., 2021). The results found in this study contradict those of Singwane and Malinga (2012) in Switzerland, who found that pine and eucalyptus plantations significantly increase organic matter and nitrogen in the soil. The accumulation of undecomposed litter of up to 50 cm was observed in the pine tree plantations signifying a slow decomposition of the organic matter to enhance soil formation.

Even though the study found that the nitrogen concentration in the soil was moderate, it was expected that the long-term presence of exotic pine, wattle and eucalyptus plantations would have greatly increased the nitrogen concentration in the soil. According to Dames et al. (2002), the cycling of nutrients in the soils under pine plantations becomes poor because a greater reserve of nutrients such as nitrogen and phosphorus is stored in the pine litter layer rather than in the soil. However, similar to the findings by Martín-Peinado et al. (2016), this study discovered that the presence of pine trees planted in the grassland over a long period of time increases the fertility of the soil compared to the grassland that is adjacent to them.

Soil Organic Carbon (SOC)

The mean percentage levels of SOC measured at each research location were 1.48 ± 0.82 in thepine plantations, 1.44 ± 0.48 in the eucalyptus plantations and 1.45 ± 0.34 in the black wattle plantations. The percentage mean of SOC found in natural forests was 3.15 ± 1.85, while in the grassland and farmlands were 1.20 ± 0.63 and 2.44 ± 1.32 respectively (Figure 2c). According to Landon (1991) and Motsara and Roy (2008), the levels of organic carbon in the soil are categorised as follows: 1.26% has a low value, 1.26% to 2.5% has medium values and >2.5% has high values. From this grouping, the soils in the study area were categorised as having low to high levels of SOC. The mean (SOC) in the pine, black wattle and eucalyptus plantations was significantly lower than that of farmlands and natural forests ($p < 0.05$), but not significantly different from that of the grassland ($P > 0.05$) as shown in Figure 2c.

The accumulation of highly degrading plant residues and microorganisms operating on a significant amount may have contributed to the high levels of SOC found in the natural forests and the farmlands compared to the exotic plantations. Contrary to the findings by Liang et al. (2016), Mengistu et al. (2022) as well as Lewis and Hossain (2022) who discovered that the exotic tree plantations increase soil organic carbon, this study found low organic carbon in these plantations, similar to the findings by Du Preez et al. (2022). Quiroz et al. (2021) found that pine plantations store much of carbon in their above-ground structures than in the below-ground soil. The slow decomposition of pine litter and low plant biomass in the black wattle and eucalyptus plantations as well as grasslands might have contributed to the low organic matter content in the underlying soils at the study sites. In addition, the low SOC content in pine and eucalyptus plantation could be due to allopathic effects of their litter, which inhibit microbial activities as reported by Hoogar et al. (2019). On the other hand, due to organic matter accumulation, a high amount of SOC was expected to be present in the old exotic tree plantations. When farmers decide to use the land that had been planted with exotic trees before for food crop production, it is suggested that they increase their crop yield by applying nitrogenous fertiliser to their fields. However, in comparison to the grasslands, the availability of soluble organic carbon increases when pine, eucalyptus and black wattle trees are planted for an extended period on the land that was formerly covered by grasslands (Quiroz et al., 2021).

Extractable Phosphorus (P)

In the pine plantations, the mean Bray-1 extractable P of the soils was 13.68 ±18.34 mg/kg, whereas in the eucalyptus plantations was 1.53 ± 1.67 mg/kg and in the black wattle plantations was 1.16 ± 0.57 mg/kg. The mean extractable P in the soil of natural forests was 2.28 ± 2.12 mg/kg, whereas those of the grassland and farmland soils were 3.61 ± 2.56 mg/kg and 3.61 ± 2.56 mg/kg respectively (Figure 2d). According to the critical range described by Landon (1991) and Motsara and Roy (2008), all soils used for the study had mean levels of extractable P below 15 mg/kg. This was the situation for all of the land uses under investigation. However, there was significantly higher extractable P in the pine plantations than in all other land uses ($p < 0.05$. The extractable P in eucalyptus and black wattle plantations had no significant differences from those of the farmlands, grasslands and natural forests ($p > 0.05$) (Figure 2d).

In spite of the fact that some of the soils in the study sites had considerable variances in the amount of extractable P, the concentration in all of the study sites was below the ideal range (less than 15 mg/kg). The low pH and high iron contents found in the soils could be a reason for the low levels of extractable P in those soils. According to Penn and Camberato (2019), the high levels of iron (Fe) and aluminium (Al) oxides that occur naturally in the soil bind the available P through strong chemical bonds, thereby reducing the amount of free P in the soil (phosphorus fixation). This occurs in acidic soil with a pH of less than 4.5. Based on this clarification, eucalyptus and black wattle plantations had no significant effect on the amount of extractable P available in the study area. These findings are comparable to those reported by Lewis and Hossain (2022), who found that there were no changes in Ca, P and toxic elements such as Al, Mn, Fe and Cd in the farms planted with the black wattle trees. In spite of the fact that eucalyptus plantations have an allelopathic effect on the microorganisms in the soil, Hoogar et al. (2019) in India reported that the amount of extractable P in these plantations was significantly higher than in unplanted areas. The study found that the pine plantations add phosphorus, similar to the study by Yin et al. (2021).

Exchangeable Bases

Exchangeable Calcium (Ca^+)

Figure 3a presents the mean levels of exchangeable Ca^{2+}, Mg^{2+} and K^+ that were found in the soils collected from various study locations. In the pine plantations, the mean exchangeable Ca^{2+} was 0.11 ± 0.04 mg/kg, while in the eucalyptus plantations soils was 0.15 ± 0.14 mg/kg and in the black wattle plantations was 0.11 ± 0.09 mg/kg. The mean exchangeable Ca^{2+} in the natural forest soil was 0.30 ± 0.35 mg/kg, whereas in the grassland and farmland soils were 0.08 ± 0.03 mg/kg and 0.34 ± 0.15 mg/kg respectively. There was a significant difference between the mean exchangeable Ca^{2+} of soils in the exotic plantations (pine, eucalyptus and black wattle) and that of the farmlands and grasslands ($p < 0.05$), but there was no a significant difference from that of the grasslands.

Exchangeable Magnesium (Mg^+)

In the pine plantations, the mean exchangeable Mg^{2+} was 0.25 ± 0.13 mg/kg, while in the eucalyptus plantations was 0.86 ± 0.72 mg/kg and in the black wattle plantations was 0.80 ± 0.58 mg/kg. The mean exchangeable Mg^{2+} in the natural forest soil was 0.58 ± 0.57 mg/kg, whereas in the grassland and farmland soils were 0.33 ± 0.23 mg/kg and 1.08 ± 0.72 mg/kg respectively (Figure 3b). There was no a significant difference between the mean concentration of Mg^{2+} in the pine plantations and that of the natural forests and grasslands. However, there was a significant difference between the mean concentration of Mg^{2+} in pine plantations and that of the farmlands ($p<0.05$). In addition, there was no a significant difference between the mean amount of Mg^{2+} in the soils under the eucalyptus and wattle plantations and that of the farmlands and natural forest soils, but it was significantly higher than that of the grasslands ($p<0.05$) (Figure 3b).

Exchangeable Potassium (K^+)

In the pine plantations, the mean exchangeable K^+ was 0.06 ± 0.02 mg/kg, while in the eucalyptus plantations was 0.19 ± 0.09 mg/kg and in the black wattle plantations was 0.15 ± 0.04 mg/kg. The exchangeable K^+ levels in the natural forest soil were 0.06 ± 0.04 mg/kg, whereas in the grassland and farmland soils were 0.06 ± 0.04 mg/kg and 0.15 ± 0.07 mg/kg respectively (Figure 3c). However, there were no significant differences between the mean of exchangeable K^+ in the soils under the pine plantations and that of the grassland and natural forest soils ($p>0.05$). However, the mean K^+ concentration in the soils beneath the eucalyptus and black wattle plantations was significantly greater than that of the grassland and natural forest soils ($p<0.05$). Still, there was no a significant difference from that of the farmland soils ($p > 0.05$) as shown in Figure 3c.

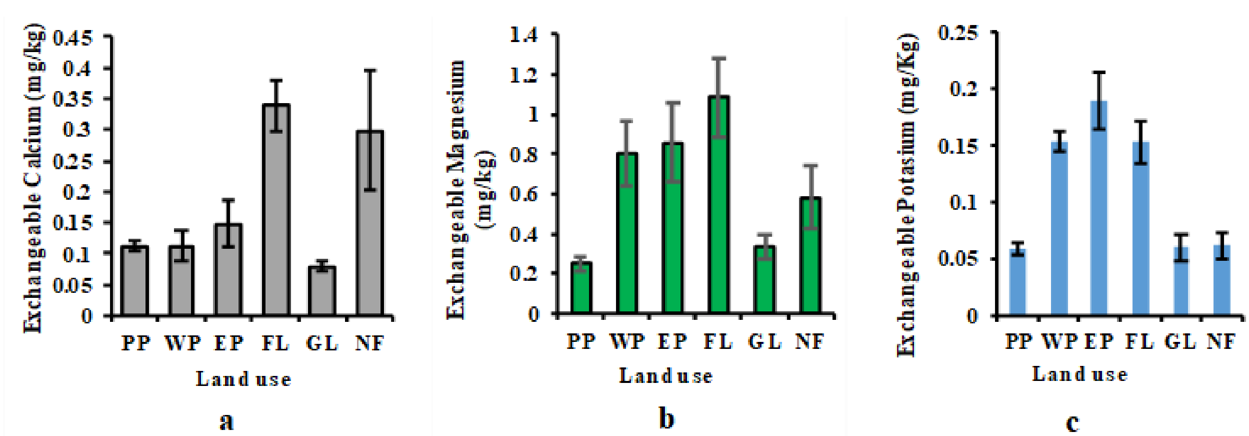

Figure 3: Comparison of the mean exchangeable bases (Ca^{2+}, Mg^{2+} and K^+) in soils of the selected land uses. (PP = Pine plantations, WP = wattle plantations, EP = eucalyptus plantation, FL = farmland, GL = grasslands, NF = Natural forests)

Source: Field work 2021

According to Thomas (1983) and Landon (1991), the average concentration of exchangeable Ca^+ and K^+ in the soils at all research sites was below the critical ranges of 2.0 mg/kg and 0.2 mg/kg respectively. Despite this, there was sufficient exchangeable Mg+ in all researched land uses (>0.2 mg/kg). Since the region is characterised by high rainfall that leads to dissolution and leaching of exchangeable bases in the soil (Singwane and Malinga, 2012; Liang et al., 2016), the low concentrations of exchangeable Ca^+ and K^+ could be due to leaching by rainwater (Kim et al., 2022). On the other hand, the mean Ca^+ concentration in natural forests and farmlands was slightly greater than that in pine, eucalyptus and black wattle plantations. This supports the findings by Mugayi (2019), who discovered significantly higher values of Ca^+ in the pine and eucalyptus plantations. However, these findings contradict the ones by Lewis and Hossain (2022), who discovered that the exchangeable Ca^+ in the soils under the black wattle plantations remained unchanged compared to the unplanted areas. The findings also contrast with those of Martín-Peinado et al. (2016), who reported a higher concentration of exchangeable K^+ in the natural forests than in the pine plantations. However, the low concentrations of exchangeable Ca^+ and K^+ observed in this study add credibility to the findings by Duffy (2014), who observed low concentrations of exchangeable bases in the areas planted with pine trees.

Micronutrients

Micronutrients were measured in the soil because they are essential for plant growth and development. These elements are needed in small quantities, but their deficiency can lead to severe problems in plant growth and crop yielding. The means of DPTA-extractable Cu, Fe, Mn and Zn in the soil used in the study have been presented in Figure 4

Copper (Cu)

Figure 4a shows that the mean quantity of copper that was extracted from the pine plantation soil by the DPTA method was 0.58 ± 0.46 mg/kg in eucalyptus plantations, 0.40 ± 0.33 mg/kg in black wattle plantations and 0.60 ± 0.37 mg/kg in pine plantations. Figure 4 shows that natural forests' mean DTPA extractable copper content was 0.51 ± 0.39 mg/kg, whereas grasslands and farmlands contained 0.68 ± 0.49 mg/kg and 0.45 ± 0.31 mg/kg respectively. However, there was no a significant difference in the mean concentration of extractable Cu between the natural forests, farmlands, or grasslands and the exotic tree plantations (p>0.05).

According to Lindsay and Norvell (1978), the critical limit of DTPA extractable copper for proper plant growth is not less than 0.2 mg/kg. Based on these limits, the soil in various land uses that were studied contained an adequate amount of extractable copper. According to the findings of this study, the presence of exotic tree plantations did not affect the concentration of extractable copper found in the soils of any of the studied sites. However, the studies by Li et al. (2020) and Kaur and Monga (2021) suggest that a considerable amount of Cu, Mn and Zn are stored in the above ground pine and eucalyptus trees, hence the trees have the ability to remove micronutrients that may be harmful when in excess. It is possible that the parent materials from which the soils were generated were responsible for the optimal extractable copper concentration that was found in the soils of the study sites.

Iron (Fe)

Figure 4b displays the mean DTPA extractable iron levels in the soils of the studied land use types in Njombe Region. These mean levels were 206.64 ± 156.27 mg/kg in the pine plantations, 243.41 ± 117.18 mg/kg in the eucalyptus plantations and 649.99 ± 496.57 mg/kg in the black wattle plantations. The mean extractable iron in the natural forests was 165.73 ± 80.38 mg/kg, while those in the farmlands and grasslands were 268.81 ± 212.59 mg/kg and 138.92 ± 64.74 mg/kg respectively. The mean content of extractable Fe in the soils of the sites covered by the pine and eucalyptus plantations did not differ significantly from that of the grasslands, farmlands and natural forests (p > 0.05). However, the soils under black wattle plantations had a significantly higher mean extractable Fe content than the soils under all other studied land uses (p <0.05).

According to Lindsay and Novell (1978), the amount of the extractable Fe that is less than 1.2 mg/kg is considered low, 1.2–3.5 mg/kg is considered medium, 3.5–6 mg/kg is considered high and >6 mg/kg is considered very high. According to this classification, the soils in all the study sites had an extremely high concentration of Fe. Both the low pH of the soil (Neina, 2019; Kim et al., 2022) and the ionic composition of the parent materials used to form the soils were thought to be related to the high levels of iron found in the soils.

Manganese (Mn)

Figure 4c contains the results of the analysis of the concentration of DTPA-extractable Mn in the soils taken from the study sites. In the pine plantations, the mean DTPA extractable Mn was 14.88 ± 8.49 mg/kg, while in eucalyptus plantations was 28.02 ± 10.42 mg/kg and in black wattle plantations was 15.98 ± 9.17 mg/kg.

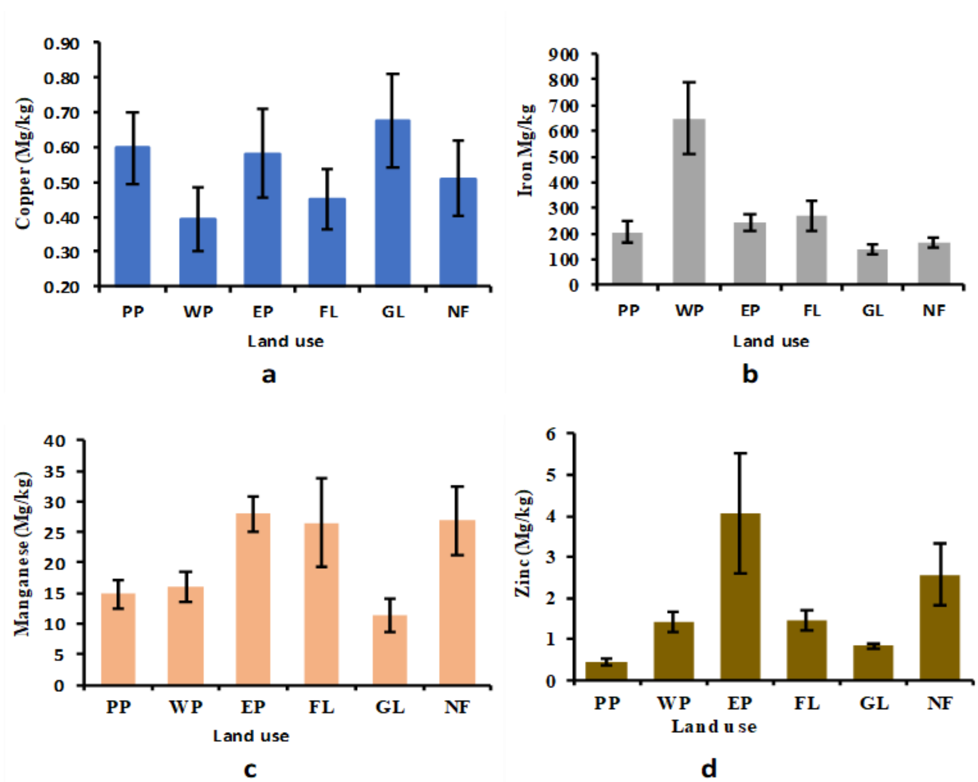

Figure 4: Comparison of micro nutrient (Cu, Fe, Mn and Zn) concentrations in soils of the selected land uses (PP = Pine plantations, WP = wattle plantations, EP = eucalyptus plantation, FL = farmland, GL = grasslands, NF = Natural forests)
Source: Field work 2021

The mean DTPA extractable Mn content in the natural forests was 26.83 ± 20.19 mg/kg, whereas in grasslands and farmlands ranged between 11.30 ± 10.09 mg/kg and 26.45 ± 26.38 mg/kg. However, there was no a significant difference in the mean content of the extractable Mn in different locations where the study was conducted ($p > 0.05$). Only the soils in eucalyptus plantations showed a significantly higher mean concentration of the extractable Mn than that in the grasslands ($p < 0.05$). The findings contradict those of Duffy (2014), who observed that the natural pine plantations had greater levels of Mn than the natural hardwood forests.

According to Lindsay and Novell (1978), the critical limit for the plant-available Mn is 1.0 mg/kg. Based on the optimal limit, the soils in all studied sites contained a sufficient amount of extractable Mn. A low soil pH that favours Mn and Zn compound dissolution in soils (Sims 1986) might have contributed to the high levels of Mn in the soil. In addition, the high Mn content in the parent materials of those soils could be one of the contributing factors for the sufficient amounts of Mn (Borkert and Cox, 1999).

Zinc (Zn)

The mean extractable zinc in the soils of the different land uses in the study area was 0.45 ± 0.25 mg/kg in the pine plantations, 4.05 ± 5.26 mg/kg in the eucalyptus plantations and 1.42 ± 0.85 mg/kg in the black wattle plantations. The grassland and farmland soils had the extractable zinc ranging between 0.84 ± 0.21 mg/kg and 1.47 ± 0.90 mg/kg respectively, while the natural forests had 2.58 ± 2.75 mg/kg (Figure 4d). The mean concentration of the extractable zinc in the soils under the pine plantations was significantly lower than that of the natural forests ($p < 0.05$), but not significantly different from that in the farmlands and the grasslands ($p > 0.05$). The mean concentration of the extractable zinc in the soils beneath the black wattle plantations was not significantly different from that of the farmlands, grasslands and natural forests ($p > 0.05$). In addition, there was no a significant difference between the mean concentration of the extractable zinc in the soils under the eucalyptus plantations and that of the natural forests ($p>0.05$), but it was significantly lower than that of the grasslands and farmlands ($p < 0.05$) (Figure 4d).

The critical range of DTPA-extractable zinc for normal plant growth is between 0.5 mg/kg and 1.0 mg/kg (Lindsay and Norvell (1978). Based on these critical levels, soils in all the examined sites had medium to high mean extractable zinc levels of 0.5 mg/kg or more, indicating a sufficient zinc availability. The sufficient availability of zinc in the soils may have been attributed to a low pH below 5 that increased the availability of zinc and Mn (Sims, 1986), as well as the parent rock of the particular area where the soil is formed (Romzaykina et al., 2021).

Conclusion

According to this study, exotic plantations–especially the pine and black wattle–lower the soil pH to below 4.0 compared to the natural forests and other types of land uses, despite the region already having high acidity ranging from 3.89 to 4.90. Even though the soil has low nutrient availability due to the high level of iron and low pH, the study found that the pine forests specifically had a higher amount of extractable P (13.68 mg/kg) than other types of land uses, which is contrary to some other studies. This suggests that pine forests add extractable P to the soil, even though the soil in the study area has a P deficiency. Additionally, the study found that the soil organic carbon was lower in the exotic forests than in other types of land uses. Since most crops grow well at a pH of 6-7.5, it is recommended that farmers use liming materials such as calcium bicarbonate (CaCO3) and magnesium carbonate (MgCO3) to raise the pH of the soil and increase nutrient availability for plant uptake when reusing tree farms for food crops after harvesting the exotic trees. In addition, farmers should use phosphate-based fertilisers like triple superphosphate (TSP) to increase the phosphorus content in the soil and improve crop yields.

Declaration of Competing Interest

The authors declare that there is no competing interest concerning the work reported in this paper.

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