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Research Article

Impacts of different exotic tree plantation forests on soil physico-chemical properties in the Central Highlands of Ethiopia

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Abstract: *This study aims to assess the impacts of plantations of different exotic tree species (Eucalyptus globulus, Cupressus lusitanica, Grevillea robusta, and Pinus patula) on soil physicochemical properties in the central highland of Ethiopia. Soil data were collected using a systematic sampling design over five different forest land-use systems. A total of 15 transect lines and 25 quadrats were used to collect soil data, with 3 transects and 5 quadrats per forest land-use system. The analysis of variance (ANOVA) for the majority of soil physico-chemical variables, including texture, moisture content (MC); bulk density (BD), particle density (PD); soil porosity (SP); organic carbon(OC); total nitrogen (TN), available P, soil pH, EC, CEC, and exchangeable bases (Ca, Mg, K, Na) showed a significant variation among forest land-use systems at ($P<0.0001$). The study findings confirmed that different exotic trees species have different effects on soil physico-chemical properties. In comparing the soil physicochemical properties among five forest land-use systems, the highest mean values of MC, OC, TN, available P, CEC, and Exch. Ca, Exch. Mg, and Exch. K was observed in natural forests. On the other hand, soil BD, PD, and EC properties in natural forests were significantly the least. In contrast, the lowest mean values of soil MC, SP, O, TN, available P, BS%, and the highest mean values of BD, PD, EC, and Exch. Na were observed under the Eucalyptus globulus plantation forest. The physico-chemical properties of soil are subject to significant changes in land use systems when different exotic tree species are grown under similar climatic conditions.*

Keywords: *Exotic tree species, Land-use systems, Plantation forest, Soil properties, Yerer forest*

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1. Introduction

Large-scale, fast-growing exotic tree species in plantation forests may have negative and positive impacts on their immediate environmental conditions, depending on the nature of individual species. A plantation forest is an area consisting of introduced plants or seedlings for afforestation or reforestation purposes (Lalisa and Hager, 2009; FAO, 2010). The worldwide areas of plantation forests are increasing from time to time, approximately from 2000 – 2020, with the annual rate of expansion of 14% (FAO, 2005; van Dijk & Keenan, 2007). The growing area of plantations can result from the demand of the world's increasing population for domestic and industrial timbers (Berthrong et al., 2009). Currently, the proliferation of fast-growing tree plantations is a global phenomenon, and plantation development is playing an increasingly important role in ecological construction and forest development. Different tree species were mainly planted to provide timber, food for humans and animals, firewood, medicines, and opportunities for recreation and tourism (Lemenih et al., 2004; FAO, 2005). Various tree species were also planted for climate and erosion control, carbon sequestration, and biodiversity conservation (Dyck 2003; Mishra et al. 2003).

Plants and soils are key components of terrestrial ecosystems, and changes in vegetation cover may lead to changes in soil properties (Binkley and Menyailo, 2005). Around 7% of the total global soil ecosystem is used for forest plantations (FAO, 2005). Soil is the dominant ecosystem that serves as the storage of transformed organic substances, mainly the recycled soil organic carbon (Lemenih et al., 2004). It is important to sustainably maintain soil quality in plantations in the context of the increasing expansion of plantation forests with introduced tree species for addressing domestic and industrial forest product needs. However, plantations can potentially alter the physical, chemical, and biological properties of the ecosystem as a consequence of changes in tree species composition when compared with their adjacent natural forests (Wall & Hytönen, 2005; Freier et al., 2010). The long-term effects of tree species on soil physical and chemical properties are critical to the future development of plantation forest policies, which must consider the selection criteria for species that meet environmental conditions, particularly soil health and quality. Vegetation affects the amount and type of organic matter added to the soil (Parker 2000, Tessema et al., 2011), and this tends to significantly affect soil structure, colour, pH, cation exchange capacity (CEC), infiltration, and water-holding capacity of soils (Ahmed, 2002).

The expansion of exotic tree species plantations in reforestation and afforestation programs is one of the highly criticized forest policies being developed in Ethiopia, mainly due to unclear, inconclusive reasons for decisions concerning their impacts on environmental conditions. Despite the increased expansion of the area used for exotic tree species plantations and their importance to human wellbeing, the implications of this on soil physicochemical properties remain an interesting topic in environmental studies. Particularly, an evaluation of soil physicochemical properties under different exotic tree species plantation covers is an important area of research to understand the impact of trees on soil properties. An increasing number of field studies have shown that soil physicochemical properties are significantly different between exotic tree species plantations and natural forests with native species. Recently, several quantitative reviews have been conducted and found significant impacts of exotic tree species plantations on soil physicochemical properties in different regions (Lemenih et al., 2004; Bekele et al., 2006; Yadesa, 2010).

Different exotic tree species are blamed for having negative effects on soil ecosystems by changing soil physicochemical properties and, hence, soil quality. Different workers were reported to contradict ideas on the impact of plantations of exotic tree species on soil physical and chemical properties change, as increases (positive), decreases (negative), or negligible (neutral) effects. These mixed field studies' results reported by different workers are preventing us from fully understanding whether exotic tree species plantations can affect soil physicochemical properties or not in the central highlands of Ethiopia (Yadesa et al. 2023). Understanding the effect of human activities on the soil's physical and chemical properties by land-use system change with different exotic species plantations is fundamental to understanding local soil change and sustainable development. Therefore, the present study aims to evaluate the impact of different exotic tree species plantations on soil physical and chemical properties, with comparison to the adjacent natural forest in the central highland of Ethiopia, to provide updated information. Specifically, this study was undertaken to address the research questions of what the impact of different exotic tree species plantation forests is on selected soil physical and chemical properties under the same ecological conditions. The research tested the hypothesis that (1) soil physicochemical properties differ significantly among studied exotic tree species plantations and natural forests, and (2) introduced exotic tree species plantations have more negative effects on soil physicochemical properties than natural forests with Indigenous tree species in the area.

2. Materials and Methods

2.1. Description of the study area

Location: This study was conducted at Yerer forest, in the east Shewa Zone, Oromia Regional State, the central highland of Ethiopia. The study area is located geographically at 8°52’00’’- 8°55’00’’ N latitude and 38°59’30’’ - 38°95’15’’ E longitude, in the east-north direction of Addis Ababa, the capital city of Ethiopia. The comparative study forest area is found in the altitudinal range from 2352 -2586 m.a.s.l. (Figure 1).

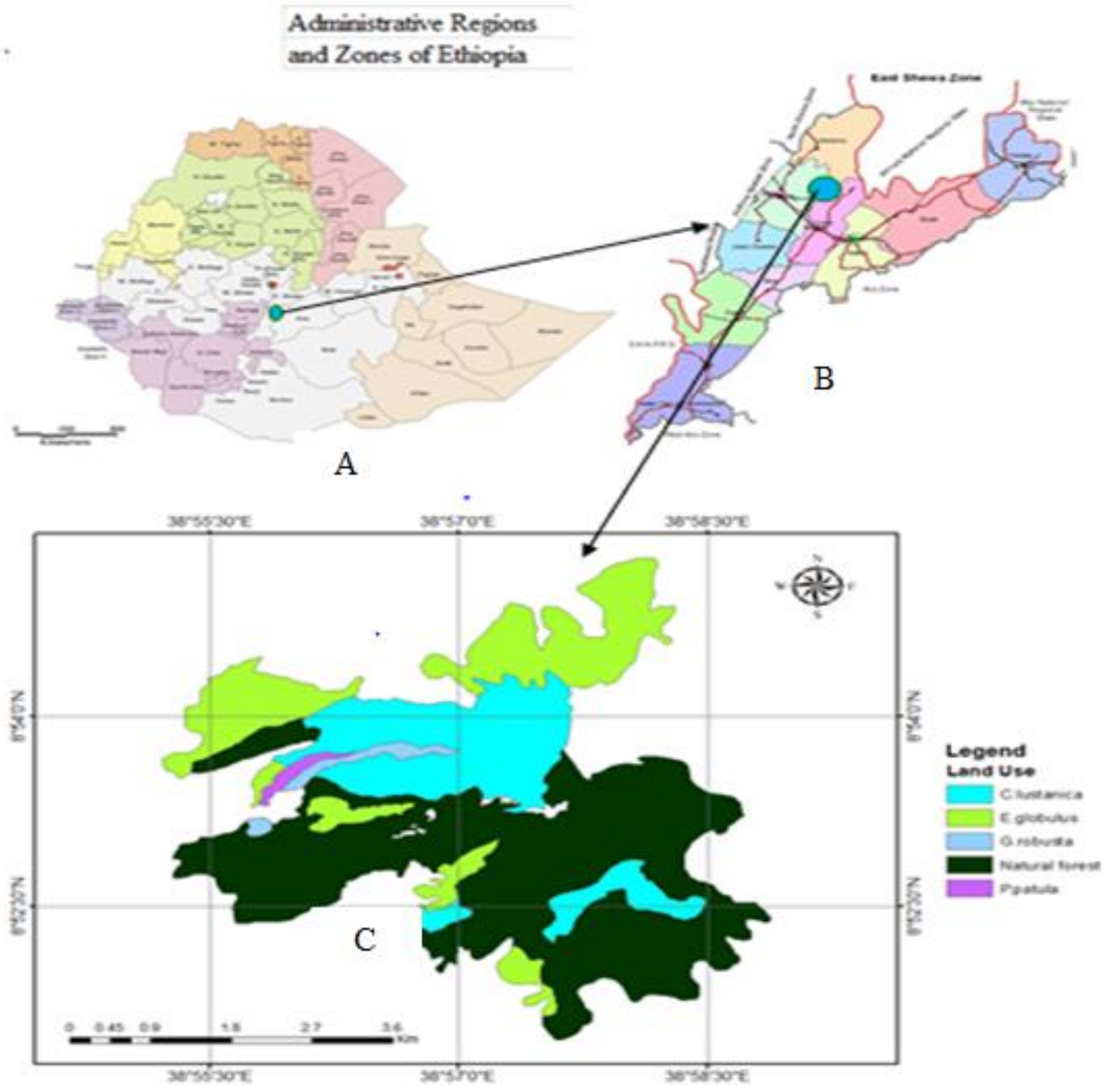

Figure 1: The image represents: A) a Map of Ethiopia, B) a Map of the East Shewa Zone in the Oromia Regional State, and C) a Map of the study area of Yerer forest (developed using ArcGIS 10.4.1 Software)

Climate: Meteorological data (1992 – 2022) showed that the mean annual rainfall of the study area is 907 mm/year, which is characterised by a bimodal rainfall having a long dry season (6-8 months). The rainfall frequency is not uniform, mostly concentrated in mid-June to early September. The mean annual minimum and maximum temperatures were 13.5 0C and 31.8 °C, respectively, National Meteorology Service Agency (2023).

Forest land-use systems: In the Yerer area, the major forest land-use systems are natural forests and exotic tree species plantation forests (*Eucalyptus globulus*, *Cupressus lusitanica*, *Pinus patula*, and *Grevillea* *robusta*) (Figure 2). In the present study context definition: A natural forest is forest land that is composed primarily of indigenous (native) trees, shrubs, lianas, climbers, and other herbaceous plant species, which may include both closed forest and open forest. Exotic tree species plantation is described as the forest stands established artificially by non-native tree or shrub species in reforestation and afforestation programs for industrial and non-industrial purposes. Yerer Mountain natural forest consists of a mixed deciduous native species forest and established plantation forests and covers an area of 3254 ha, of which 1793 ha is plantation forest, and 1461 ha is covered by natural forest and others. Before 1999, Yerer's natural and plantation forest area land-use type had free open scattered remnant secondary woodland, which was considered a vital degradation place. Yerer's natural forest and plantation forest were designated, demarcated, established, and started to be managed in 1999 as the “environmental conservation and Fuelwood plant development” forest area, which was administered by the “Addis Ababa and Bahir-Dari Fuelwood Plant Development Agency” under the Ministry of Agriculture.

The main objective of Yerer's natural and plantation forest management and conservation was to provide fuel wood and construction materials to urban and city people to satisfy the energy demand. The comparative study of all forest land-use systems is laid between 2352 -2586 m.a.s.l., and 3–12% altitudinal and slope range, respectively. The land on which the exotic species of *Eucalyptus globulus*, *Cupressus lusitanica*, *Pinus patula*, and *Grevillea robusta* were planted on degraded remnants of natural forest land. The age of the natural forest is about 26 years, but the plantation forests are between 15 and 19 years old, under similar management practices. In general, the diameter, height, and basal area of woody species vary among different plantation exotic tree species throughout the study area. The nature of the soil type under all forest land-use systems is characterized as a clay-loam soil type in the area.

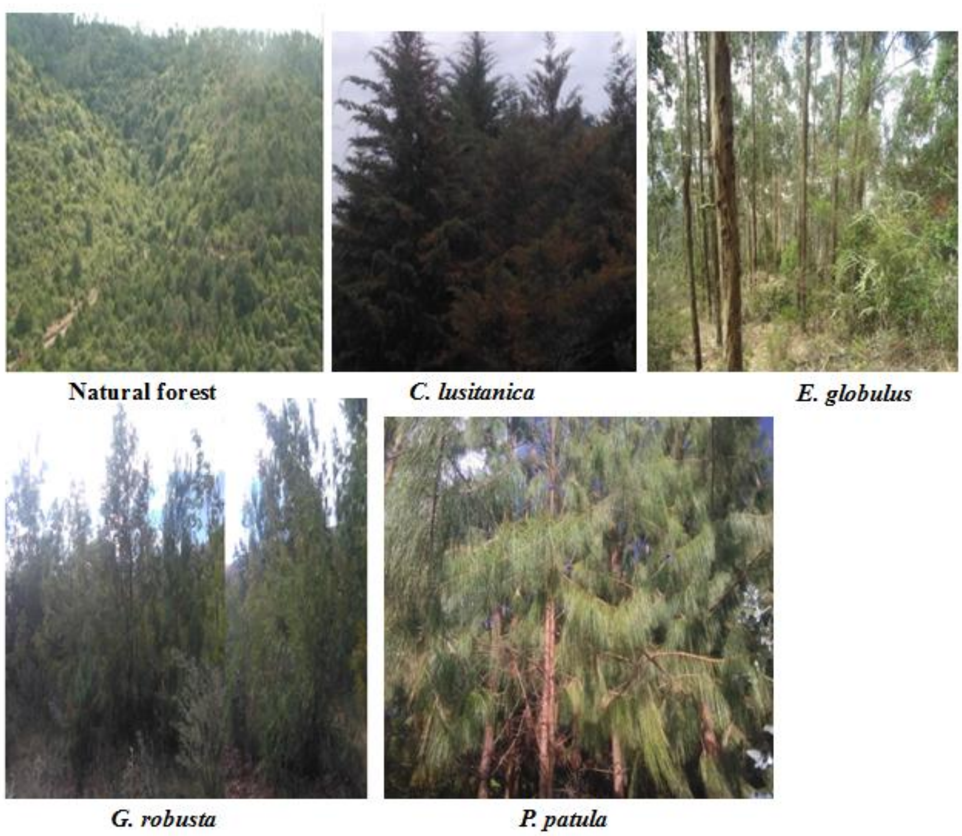

Figure 2: Images represent: the five different forest land-use systems in the Yerer area, a central highland of Ethiopia

2.2. Sampling design and procedure

2.2.1. Sampling design

Different forest land-use systems (FLUSs) were selected, namely: natural forests, and four exotic tree plantation species (*Eucalyptus globulus, Cupressus lusitanica, Grevillea robusta*, and *Pinus patula*) (Figure 2). In this study, the five forest land-use systems (FLUSs) were considered as treatments, and the quadrat samples in each FLU were considered as a replication. A systematic sampling design was used to determine the soil physico-chemical properties, with transect lines laid in each FLU. In each forest land-use system (FLUS), three transect lines were drawn separately along the altitudinal gradient and laid parallel to each other. The soil samples were collected by arranging the sample quadrats at a 50-meter distance between two adjacent transect lines, and between the consecutive intervals of quadrats on a transect line to avoid biased sample selection.

2.2.2. Soil sampling procedure

Soil data collection was done from relatively similar forest land-use systems (FLUSs) in terms of topography, altitude, aspect, slope, and areas free from erosion. For soil data collection, the main square sample quadrat of 20 m x 20 m (400m2) area was established with five replication quadrats in each forest land-use system. The soil samples were collected in five replicates of subquadrats with a 1m x 1m area within each main square quadrat of 20m x 20m area, by arranging four (4) subquadrats at each corner and one (1) at the centre of the main quadrat in each forest land-use system. The soil samples were collected from two depth layers of topsoil (0 – 20 cm) and subsoil (20 – 40 cm). Soil samples were taken by using a soil auger at the center of each sub-quadrat of a 1m x 1m area. The soil samples were collected by using a soil auger in accordance with the required soil depth layers and by carefully cleaning the equipment at each soil sampling depth, to prevent soil contamination between depth layers and quadrats.

2.3. Soil analysis and laboratory procedure

2.3.1. Analysis of soil physical properties

The soil texture classes (% sand, % silt, and % clay) were analyzed by using the Hydrometer method. This method is preferable due to its inexpensiveness, ease, and rapidity of use in a soil laboratory. In the hydrometer method, 40 g of sodium hexametaphosphate and 10 g of sodium carbonate were dissolved to make a volume of 1 liter by adding distilled water to be used as a dispersing agent. Fifty-one grams of an air-dried soil sample were added to 50 ml of a dispersing agent and 100 ml of distilled water. The contents were mixed with a glass rod and allowed to stand for 30 minutes. Hydrometer and temperature readings were taken after 40 seconds and 3 hours, following the procedure stated by Brady and Weil (2002).

Soil moisture content was determined by weighing fresh soil samples in a laboratory immediately from the field fresh sample and again reweighing soil samples after oven-drying at 105 0C for 24 hours in the laboratory (Brady and Weil 2002). The moisture content of each sample was computed by subtracting the dried weight of the soil sample from the corresponding fresh sample weight. For soil bulk density determination, undisturbed soil samples of known dimensions (length and diameter) and volume were taken with a Core sampler tool forced manually into the center of the required soil depth. For bulk density determination, the samples were dried in an oven at 105°C (221°F) for a minimum of 48 hours. Subsequently, bulk density was calculated from the measurement of bulk volume used in the core length and the diameter of the cutting edge of the core sampler (Black et al., 1965).

2.3.2. Analysis of soil chemical properties

Ranst et al. (1999) described the Walkley Black wetting approach as an indicator of soil organic carbon (OC). The modified Kjeldahl's digestion, distillation, and titration method was used to determine the total nitrogen level in the soil Ranst et al., 1999). The C: N ratio was determined by dividing the value of organic carbon by the total nitrogen corresponding to each soil sampling depth. The soil's available phosphorus content was determined by following the Olsen procedure (Olsen et al. 1954). A digital pH meter was used to measure the soil's pH in a suspension of 1:2.5 soil-to-water supernatant (Jackson, 1973; Van Reewijk, 1992). The electrical conductivity of the soil samples was determined by using an electrical conductivity meter from a 1:1 soil-distilled water mixture (20g of soil in 20 ml distilled water) (Ranst et al. 1999). By combining 1N sodium acetate and substituting the sodium on the exchange complex with 1N ammonium acetate at pH 7, soils were evaluated for their cation exchange capacity (CEC) using Chapman's method (1965). Sodium concentration in soil was measured by atomic absorption spectrometry (AAS), and CEC was expressed as meq/ 100g of soil. Extraction of exchangeable bases was carried out using 1M ammonium acetate at PH 7.0.15. Exchangeable Ca and Mg were measured from the extract with an atomic absorption spectrophotometer, whereas exchangeable Na and K were determined from the same extraction with a flame photometer (Black et al., 1965). Percent base saturation (PBS) was determined by dividing total exchangeable bases (Ca, Mg, K, and Na) by the CEC of the soil and multiplying by 100.

2.4. Data Analysis

The recorded value of soil parameters was first compiled and tabulated in Microsoft Excel Professional Plus 2010. The general linear model (GLM) ANOVA procedure of the statistical analysis system SAS (2004) was used to determine the significance of differences in soil parameters. The data were subjected to a one-way Analysis of Variance (ANOVA), and significant means were separated using the Least Significant Difference (LSD) Test at a 5% level of significance as described by Shrestha (2019). Means comparisons were used to soil properties change interpretation and explanation among the five forest land-use systems in the study area.

3. Results and Discussion

3.1. Soil physical properties under different exotic tree species plantations and natural forests

3.1.1. Soil texture

The soil textural fractions of sand, silt, and clay significantly varied with different forest land-use systems. The analysis of variance for sand content of the soil revealed significant differences horizontally as a function of forest land-use systems (P<0.0001). The particle size distribution data showed that the maximum sand content was observed in the *Cupressus lusitanica* plantation forest (43.80%), followed by natural forest (40.70 %) and *Eucalyptus globulus* plantation forest (37.70%) land-use systems (Table 1). There was a significant difference (P<0.01) in soil clay contents among forest land-use systems.

Table 1: Mean values of selected soil physical properties under different forest land-use systems

Land-use systems	Sand (%)	Clay (%)	Silt (%)	Textural class	MC %	BD (gm/cm^3)	PD (gm/cm^3)	SP (%)
Natural forest	40.70^a	33.90^b	25.40^{ba}	Clay Loam	23.08^a	1.17^b	1.72^{cd}	0.32^a
E. globulus	37.70^a	37.70^{ba}	24.60^b	Clay Loam	17.00^c	1.81^a	2.11^a	0.14^c
C. lusitanica	43.80^a	34.30^b	21.90^b	Clay Loam	20.92^b	1.31^b	1.90^{cb}	0.31^{ba}
G. robusta	36.80^b	38.30^{ba}	24.30^b	Clay Loam	22.74^{ba}	1.29^b	1.97^b	0.34^a
P. patula	28.00^c	42.10^a	29.90^a	Clay	21.28^{ba}	1.19^b	1.62^d	0.27^b
LSD	6.58	5.60	5.05	-	1.81	0.15	0.20	0.05
CV	20.04	16.92	21.71	-	10.07	11.61	10.83	17.65
Sign.	0.0001***	0.01*	0.03*	-	0.0001***	0.0001***	0.0001***	0.0001***

Means within a column followed by the same letter are not significantly different at p < 0.05; *** = very highly significant; ** = highly significant; * = significant; ns = non-significant**.** MC = moisture content; BD = bulk density; PD = particle density; % = percent; gm = gram; cm = centimeter

The study area soil textural class is grouped as clay-loam. However, the higher sand proportion (43.80%) was observed in the *Cupressus lusitanica* plantation forest than in the other land-use systems (LUS). *Cupressus lusitanica* plantations have a higher proportion of sandy soil than other species, which is most likely owing to a combination of factors relating to the tree's growth characteristics and impact on soil, by means of it's a dense canopy which related with high transpiration rates, lower soil organic matter (SOM) contents in relate to soil-forming process, which might result to modify soil structure and composition over time, promoting the development of sandy soil properties in dry soil conditions, especially after rain. Similar study results have been reported by Michelsen et al. (1993) and Mulugeta et al. (2004). However, among the forest land-use systems (FLUS), the contents of the minimum sand were recorded in the *Pinus patula* plantation forest (28.0%). The variation in the amount of sand proportion among land-use systems might be due to the influence of different forest land-use systems on the weathering processes of soil formation by the accumulation of particles under vegetation.

Among forest LUS, the maximum and minimum mean values of small-sized soil particles (clay) were observed in the plantation exotic tree species of *Pinus patula* (42.10%) and natural forest (33.9%), respectively. The variation of the relative percentage of clay particles between *Pinus patula* plantation forest and natural forest might be influenced by a combination of factors related to variations in organic matter input, water infiltration, and the influence of different tree species' potential on nitrogen cycling, which leads to altering clay content through soil structure and aggregation formation. In line with the present finding, Fantaw et al. (2007), Michelsen et al. (1993) also stated that vegetation types and their density attributed to influence the relative soil particle density under different land-use types.

As a function of the land-use systems factor, the maximum mean values of silt contents were recorded in *Pinus patula* plantation forest (29.90%), whereas the minimum mean value of silt content was observed in *Cupressus lusitanica* plantation forest (21.90%). The variation of silt soil particles across forest land-use systems (FLUS) might have happened due to the process of pedogenesis or soil formation, vegetation type, and plant density cover. In *Pinus patula* plantation forest due to a species that produces high litter fall biomass on the ground might be decomposed via the action of micro-organisms and form soil silt particles. This suggestion was supported by the highest average litter depth (4.20 cm) accumulation recorded in *the Pinus patula* plantation forest during the study. Similarly, different workers of Tsehaye and Mohammed (2013), Fantaw et al. (2007), and Michelsen et al. (1993) reported the varying amount of silt contents under different land-use types in Ethiopia.

3.1.2. Soil moisture content, bulk density, particle density, and porosity

The analysis of the variance of moisture content, bulk density, and particle density of the soil revealed a significant influence of forest land-use systems ($P < 0.0001$). The soil moisture distribution ranged in all forest land-use systems from 16.51 to 23.08% with an order of natural forest > *G. robusta* > *P. patula* > *C. lusitanica* > *E. globulus* (Table 1). In the assessments of soil moisture content levels under different land-use systems, the obtained results showed that maximum mean values of moisture contents were recorded in natural forest (23.08%), and *Grevillea robusta* plantation forest (22.74%) without significant differences between them as compared to the other land use systems (LUS). This may be attributed to different factors of the higher accumulation of organic matter with litter's deposition, which contributes to the maintenance /improvement of soil structure, porosity, water infiltration, water holding capacity, reducing soil erosion, and reducing evaporation rate, thereby contributing to increasing soil water retention capacity. Similar observations were reported by Gol (2009) and Rahman et al. (2012). Similarly, Soil texture may greatly influence the water-holding capacity of the soils through improving water infiltration, permeability, and porosity of soils. Therefore, the study area soil textural class clay loam particles have many small pore spaces that make water move slower leading to the highest water holding capacity. This argument is supported by a positive correlation that existed between soil moisture with organic carbon ($r = 0.320$), moisture with clay ($r = 0.028$), and moisture with silts ($r = 0.158$) relationships.

The minimum moisture contents were recorded in the *Eucalyptus globulus* plantation forest (16.99%). This is probably due to the lower accumulation of organic matter with litter felled, which contributes to low-quality soil structure formation, less water infiltration, and low water holding capacity. For this observation, the reasons may be due to the fast-growing *E. globulus* species consuming more water in the soils, high evaporation rate due to open canopy, low surface cover by litter, and low water infiltration and permeability due to soil compaction because of high soil bulk density registered under it.

Regarding the relationship, soil moisture content was negatively correlated with bulk density (r = - 0.354) under the *Eucalyptus globulus* plantation forest. Similar findings were reported by Kakaire et al. (2015) and Aweto and Moleele (2005).

The bulk density values varied in response to land-use systems. In the study area, the mean values of bulk density ranged from 1.17 to 1.81 g/cm3 under different land-use systems (Table 1). As the function of land-use systems, the overall proportional distribution of particle density was observed in the order of *E. globulus* > *G. robusta* > *C. lusitanica* > natural forest and *P. patula* plantation forest. Without a significant difference, the higher mean values of porosity of the soil were recorded in *Grevillea robusta* plantation (0.34) and natural forest (0.32). The present study indicated that the lower mean values of bulk density of the soil were recorded in a natural forest, *Pinus patula*, and *Grevillea robusta* plantation forests in the order of 1.167 g/cm^3, 1.193 g/cm^3, and 1.292 g/cm^3, respectively, without significant difference among them. The reason may be due to the difference in soil organic matter (OM) content among land-use systems. The lower bulk density is attributed to the higher organic matter accumulation under the canopy, which leads to an increase in the soil looseness, porosity, and well-aggregated, and, thereby, results in lower bulk density. This argument is by the negative correlation that exists between bulk density and soil organic carbon (r = -0.403). In line with the present finding, Mostafa et al. (2008), Gol (2009), Kaur and Toor (2012), Mulugeta (2014), Maqbool etal. (2017), Tellen, and Yerima (2018) reported similar findings in different areas. On the other hand, the highest mean value of bulk density of the soil was recorded in the *Eucalyptus globulus* plantation forest (1.81 g/cm^3). This is probably due to the soil compaction encountered as a result of lower organic matter accumulation and large sand proportions. This argument is by the positive correlation that exists between bulk density and sand (r = 0.2153), and a negative correlation between bulk density and organic carbon (r = -0.279). Similarly, Michelsen et al. (1993) observed high bulk density under the *Eucalyptus globulus* plantation forest at 0-40cm soil depth in central highland Ethiopia.

The inconsistency in particle density means values among forest land-use systems in the study area may be due to the inherent differences among the land-use patterns. The lower mean values of the particle density of the soil were recorded in the natural forest (1.620g/cm^3) and *Pinus patula* plantation forest (1.620g/cm^3). This may be attributed to the effect of the high accumulation of organic matter by litter's deposition in soil contributes to the maintenance of soil structure and porosity, leading to decreased particle density. This explanation is supported by the negative correlation between particle density with organic carbon (r = - 0.4742), and porosity (r = - 0.1785). In line with the present findings, similarly, the other workers of Maqbool et al. (2017), Woldeamlak and Stroosnijder (2003), and Watt et al. (2005) observed the lowest soil particle density in natural forest than plantation forest land-use systems.

On the other hand, the highest mean value of particle density of the soil was recorded in the *Eucalyptus globulus* plantation forest (2.11 g/cm^3). This is probably due to the effect of low organic matter addition from woody litter and herbaceous residuals, low CEC, and low pH (acidity) levels under the *Eucalyptus globulus* plantation forest. A low cation exchange capacity (CEC) and an acidic soil pH can indirectly raise soil particle density, chiefly by influencing the stability of soil aggregates and the level of organic matter. Additionally, higher soil particle density may be attributed to the higher amount of heavy minerals like iron compounds, if present in the soil also contributes to increasing the particle density under *Eucalyptus globulus* plantation forest than other land-use systems. Similar to the present finding, Mulugeta (2014) and Michelsen et al. (1996) also observed the different relative soil particles under various land-use types.

The higher mean values of porosity of the soil were registered in *Grevillea robusta* plantation and natural forest land-use systems. This may be attributed to the higher organic matter deposition, which contributes to binding large soil particles into aggregates to make many smaller pore spaces or open spaces, and greater pore interconnectivity between larger particles in the soil leads to increased soil porosity and water-holding capacity of the soil. This argument is supported by the positive correlation between porosity and organic carbon (r = 0.107). Comparably, Mohammed et al. (2005) and Wakene (2001) reported similar findings for the soils of the Chercher highlands and the Bako area of Ethiopia.

Among the forest land-use systems, the lower mean values of soil porosity were registered under the *Eucalyptus globulus (*0.14) and *Pinus patula* (0.27) plantation forests. This may occur due to the lower organic matter addition or the removal of organic matter litter from the site by collecting firewood from the ground, which may contribute to making fewer binds of large soil particles into aggregates, and lesser pore interconnectivity between larger particles in the soil leads to a decline in soil porosity. The higher bulk density may also reduce the porosity of the soil, which hinders the movement of water and minerals in the soil (Mulugeta 2014). Similar studies reported that bulk density values were inversely related to soil porosity, as high bulk density resulted in lower total soil porosity (Igwe, 2005).

3.2. Soil chemical properties under different exotic tree species plantations and natural forests

3.2.1. Soil organic C, total N, C:N ratio, and available P

The soil analysis results for the Soil Organic C, Total N, C: N ratio, and Available P are statistically summarized in Table 2. The analysis of variance for organic carbon concentration of the soil revealed that the natural forest and *Grevillea robusta* FLUSs were significantly different from the remaining three forest land-use systems (FLUSs) horizontally as a function of land-use systems (p<0001). Among the different forest land-use systems, the organic carbon concentration levels were observed in the order of natural forest > *G. robusta* > *P. patula* > *C. lusitanica* > *E. globulus*. The overall mean value of the organic carbon concentration under the five different forest land-use systems varied between 2.03 to 3.49% (Table 2).

Higher organic carbon concentration levels were observed in natural forests and *Grevillea robusta* plantation forests. This is probably due to the higher accumulation of soil organic matter (SOM) by litter from different heterogeneous plant species with a high rate of biomass production, and better carbon nutrient mineralization to the soils through decomposition. Other workers of Michelsen et al. (1996), Mulugeta et al. (2004), and Bekele et al. (2006) reported similar findings in different regions of Ethiopia. However, among the forest land-use systems in the study area, the minimum value of organic carbon concentration was observed in *the Eucalyptus globulus* plantation (2.03 % DM). The difference could be attributed to the addition of lower organic matter to the soil via litter inputs and losses of organic matter through the harvesting of litter biomass from sites. Organic carbon contents were highly affected by soil texture and slightly by land-use systems. This argument is supported by the soil organic carbon that negatively correlated with the soil texture of clay (r = - 0.340) and silt (r = - 0.106). The results were in agreement with the findings of Wakene (2001), Mulugeta et al. (2004), and Lalisa. Et al. (2010), Mulugeta (2014), Wasihun etal. (2015), and Tellen and Yerima (2018) reported less organic carbon in *Eucalyptus* plantations than in other land-use systems.

Statistically, the total nitrogen content of the soil showed a significant variation as a function of forest land-use systems (p<0.0001). The overall mean value of the total nitrogen levels in all different forest land-use systems varied between 0.17 to 0.31 % ranges (Table 2). The overall ANOVA analysis of C: N ratios revealed that there was a non-significant (p < 0.05) influence of any forest land-use systems. The overall mean value of the C: N ratios under five different forest land-use systems were found between the 11.38 and 12.08 ranges. The C: N ratio was significantly narrowed from 11.38 in the natural forest to 12.08 in the Pinus patula plantation soils.

The highest mean value of total nitrogen content was observed in the natural forest (0.31% DM), followed by the *Grevillea robusta* plantation (0.26% DM), with significant statistical differences between them. These might be attributed to the long–term accumulation of above and below-ground organic matter inputs from litter fall, root turnover, mineralization by actions of soil microbes, and N fixation by symbiotic in leguminous plant species diversity in natural forests and other soil microorganisms. This argument is supported by the strong positive correlation (r = 0.947) between the total nitrogen and organic carbon. Similar studies were also reported as the higher total nitrogen content was observed in the natural forest than in other forest land-use systems in different areas (Michelsen et al., 1996, Mulugeta et al., 2004, Bekele et al., 2006, Mulugeta, 2014, Tellen and Yerima, 2018). On the contrary, the lowest mean value of total nitrogen content was observed in *the Eucalyptus globulus* plantation (0.17% DM). The reasons for the lower total nitrogen content may be attributed to the loss of nitrogen either to the atmosphere by evaporation or leached down by the water. Because there is no real store of available nitrates in the soil, as nitrates are released from organic matter breakdown unless they are used by plants. Similarly, other workers of Michelsen et al. (1996), Mulugeta et al. (2004), and Lalisa et al. (2010) have also reported lower total nitrogen concentrations under *Eucalyptus* plantation forests than other land-use systems in different regions of Ethiopia.

The lowest value of the C: N ratio was observed in the natural forest. This may be attributed to the increasing nitrogen nutrient inputs, with a high rate of nitrogen fixation by different leguminous plant species diversity, with relatively higher protein and nutrient contents in the natural forest, which leads to the lower C: N ratio, due to their fast decomposition rate and release of nitrogen to the soil. Faster decomposition of leaf litter enhances the transfer of fresh carbon to mineral soil. Similarly, different workers have reported that the lower C: N ratio under different native plant species (Abebe et al., 2009; Tadesse et al., 2000, and Yadesa, 2010).

The highest C: N ratio (12.08) was found in the vicinity of *the Pinus patula* plantation. This may be attributed to lower nitrogen and higher organic carbon contents in the litter of organic matter, which results in a higher C: N ratio and slow decomposition rate. The optimum C: N ratio (less than 20:1) ensures that the soil has a suitable energy reserve as well as tissue-building material to enable the plants to thrive. Plant residue with a low C/N ratio (high nitrogen content) decomposes more quickly than plant residue with a high C/N ratio (high carbon content) and does not increase soil organic matter accumulation levels as quickly, because of the immediate supply of mineralized N for crop growth by fast decomposition processes (Janssen 1996, Bengtsson et al., 2003; Springob and Kirchmann, 2003).

The overall available phosphorus concentration level under different forest land-use systems was observed in the range between 2.45 and 31.52 mg/kg of soil (Table 2). The concentration of available phosphorus levels was found in the order of natural forest > *P. patula* > *G. robusta* > *E. globulus* > *C. lusitanica* forest land-use systems

The variation of available phosphorus concentration levels among forest land-use systems was determined, and the total phosphorus concentration in natural forests (31.52 mg/kg of soil) was higher than that found in other land-use systems. This may be due to the higher accumulation of organic matter. The main natural source of phosphate in many soils is the breakdown of organic matter or decomposition via the action of microorganisms that release available phosphorus into the soil. This argument is supported by the simple linear correlation relationships between available phosphorus and organic carbon were positively correlated (r = 0.547). Similarly, other workers have also reported a higher concentration of available phosphorus in the natural forest than other land-use systems (Michelsen et al., 1996, Nsabimana et al., 2008, Mulugeta, 2014).

The lower mean values of available phosphorus concentration were recorded in *Cupressus lusitanica* (2.45) and *Eucalyptus globulus* (3.12) plantation forests. This may be attributed to the fast-growing tree plantation species being associated with a more intense uptake of nutrients from the soil than slow-growing forest species. Additionally, the lower available phosphorus concentration under *C. lusitanica* and *E. globulus* plantation may be due to the loss of organic matter by rotational harvesting and taken away from the site, which is related to management practices. Michelsen et al. (1993) and Lisanework and Michelsen (1994) noted that phosphorus (P) concentration was limited by plant growth and leaf litter decomposition under *C. lusitanica* and *E. globulus* plantations in Ethiopia.

Table 2: Mean values of selected soil chemical properties under different forest land-use systems

Land-use systems	OC (%DM)	Total N (% DM)	C: N ratio	Avail. P (mg/kg of soil)	PH-H_2O (1:2.5)	EC (ds/m)	CEC (meq/ 100 mg)
Natural forest	3.49[a]	0.31[a]	11.38[a]	31.52[a]	6.20[a]	1.78[c]	33.63[a]
Eucalyptus globulus	2.03[c]	0.17 [c]	11.87[a]	3.12[c]	5.48[bc]	3.47[a]	25.78[cb]
Cupressus lusitanica	2.29[cb]	0.20[c]	11.75[a]	2.45[c]	5.41[c]	2.34[b]	21.26[d]
Grevillea robusta	3.14[a]	0.26[b]	12.03[a]	5.82[c]	5.70[bac]	2.42[b]	23.24[c]
Pinus patula	2.54[b]	0.22[bc]	12.08[a]	20.32[b]	5.99[b]	2.35[b]	29.23[b]
LSD	0.50	0.05	1.42	8.31	0.49	0.56	3.49
CV	24.61	26.13	13.48	77.13	9.44	26.50	15.02
Sign.	0.0001	0.0001	0.1094	0.0001	0.0595	0.0002	0.0001

Means within a column followed by the same letter are not significantly different at $p < 0.05$; CEC = Cation exchange capacity; *** = very highly significant; ** = highly significant; * = significant; ns = non-significant

3.2.2. Soil pH, EC (ds/m), and CEC

Soil pH is one of the soil chemical properties which is used to measure the acidity or alkalinity of the soil. The analysis of variance for soil pH revealed a significant difference as a function of forest land-use systems (p<0.0001) except between *Eucalyptus globulus* and *Cupressus lusitanica*. The overall mean value of soil pH level distribution in different forest land-use systems was observed in the order of natural forest > *P. patula* > *G. robusta* > *E. globulus* > *C. lusitanica* (Table 2). The lower mean values of soil pH were recorded in *Cupressus lusitanica* and *Eucalyptus globulus* plantations in the orders of 5.41 and 5.48, respectively, without significant differences between them.

Among the forest land-use systems, the maximum mean value of pH (6.20) was observed in natural forests with a significant difference from the others. This might be attributable to the higher litter deposition from the aboveground and belowground (roots), which have undergone decomposition by the action of micro-organisms and subsequent mineralization to release basic cations to the soil in natural forest land-use systems. This agrees with the simple positive correlation relationships between soil pH with soil organic carbon (r = 0.432), with cation exchange capacity (CEC) (r = 0.649), with exchangeable cations of Ca (r = 0.592), Mg (r = 0.26062), K (r = 0.3253), and negative correlation with Na (r = -0.101) in the soils. Similar study results were reported by Michelsen et al. (1993), Michelsen et al. (1996), and Nsabimana et al. (2008) for soils of higher pH levels under natural forests than other land-use systems.

The main reasons for the lowest value of soil pH in the *Cupressus lusitanica* and *Eucalyptus globulus* plantations could be due to lower accumulation of soil organic matter (SOM) by adding a few litters to soils from mono exotic tree plantation species, low basic cations release to soils, and prolonged uptakes of basic cations from soils by fast-growing plantation tree species roots. Additional reasons may be that fast-growing exotic plantations acidify the soil in nature by accumulating excess basic cations in the forest biomass, increasing the production of organic acids from decomposing litter, and increasing cation leaching. The fast-growing exotic tree species that require high water for biomass production may increase solute concentrations and the mineralization of organic sulfur in the soil, which leads to decreased soil pH. Soil pH decreased in plantation forests where exotic trees grow quickly (Jobbágy and Jackson, 2003; Mishra et al, 2003; Sanchez et al., 2003; Nsabimana et al, 2008, Tegenu et al., 2008, Tellen and Yerima, 2018).

The statistical analysis for soil electrical conductivity revealed a significant variation among forest land-use systems (P<0.0001) except between *Grevillea robusta* and *Pinus patula*. The overall mean values of soil electrical conductivity (EC) distribution under different forest land-use systems varied between 1.78 and 3.47 ds/m. Among all forest land-use systems, the maximum and minimum mean values in soil electrical conductivity (EC) were observed in *Eucalyptus globulus* plantation forest and natural forest, respectively (Table 2). A lower pH indicates that a higher concentration of hydrogen ions, which contribute to electrical conductivity due to the presence and mobility of H+ ions.

According to the current finding, the mean value of electrical conductivity (EC) of soil levels across land-use systems was found in the order of *E. globulus*,> *G. robusta*,> *P. patula*,> *C. lusitanica*,> natural forest. The higher value of EC under *Eucalyptus globulus* plantation may be attributed to the soil compaction related to high bulk density, lower soil moisture content related to soluble salts accumulating in the upper soils rather than leached down, high evaporation rate due to open canopy and low infiltration rate, salts originate from the disintegration (weathering) of minerals and rocks, soils with an accumulation of exchangeable sodium are often characterized by poor tilth and low permeability making high EC. These reasons are supported by the positive correlation between the electrical conductivity (EC) and exchangeable sodium, Na (r = 0.202), bulk density (r = 0.433), and negative correlation with moisture content (r = -0.265), porosity (r = -0.264), and organic carbon (r = -0.466). In line with the present finding, Michelsen et al. (1996) also observed a higher mean value of electrical conductivity (EC) and bulk density of soil beneath the *E. globulus* species than the other forest tree species.

The minimum mean value of electrical conductivity (1.783) was observed in the natural forest than the other plantation forest land-use systems. The lower level of EC under natural forests is probably attributed to the higher accumulation of organic matter (litter deposition) that decomposed and released higher exchangeable cations (K, Ca, Mg) to the soils, which led to a reduction in the salinity level in the soils. The variation in high litter fall addition or organic matter accumulation was decomposed and released exchangeable cations to the soil, which leads to lower values of electric conductivity under the natural forest. This explanation is supported by the negative correlation between electrical conductivity and exchangeable cations K (r = -0.400), Ca (r = -0.532), Mg (r = -0.173), and organic carbon (r = -0.466). Comparably, Michelsen et al. (1996) and Gol (2009) reported similar findings by observing a lower mean value of electrical conductivity under natural forests than in other land-use systems.

The analysis of variance (ANOVA) for cation exchange capacity (CEC) showed a significant variation among Natural forest, *Grevillea robusta*, and *Pinus patula* forest land-use systems (P<0.0001). The present study showed that the mean values of CEC were found between 18.98 and 33.63 meq/100 g of soil. The overall mean value of soil CEC level distribution in different land-use systems was recorded in the order of natural forest > *P. patula* > *E. globulus* > *G. robusta* > *C. lusitanica*.

Natural forests (33.63 meq/100 mg) have the highest cation exchange capacity (CEC) among all forest land-use systems. This is probably influenced by the high amount of clay contents, organic matter accumulation, and high soil pH in the natural forest, which lead to higher CEC. This means the CEC of soils is affected mainly by the amount and type of clay and the amount and degree of decomposition of the organic matter. In general, the higher soil organic matter (SOM) and clay content result in a higher CEC. This reason is supported by a significant positive correlation between the soil's CEC and OC (r = 0.644), clay (r = 0.184), and pH (r = 0.649). The CEC is positively correlated with pH; therefore, acid soils have a lower potential for CEC. The present results agree with the findings of Michelsen et al.(1996), Dhaliwal and Singh(2003), Mulugeta et al.(2004), Nsabimana et al.(2008), and Habtamu etal.(2018), were observed the highest cation exchange capacity (CEC) values in the natural forest than in other land-use systems in different areas.

3.2.3. Soil Exchangeable bases and Base saturation percent

As the function of forest land-use systems, the concentration of exchangeable cations was generally in the order of Ca > Mg > K > Na in all different forest land-use systems of soils (Table 3). These results agree with the principle stated as the energy of the adsorption sequence of Ca > Mg > K > Na. The highest concentration of exchangeable cations of Ca, Mg, and K was observed in the natural forest in the order of 17.13, 5.37, and 3.60 cmol (+)/kg soil, respectively.

Table 3: Mean values of selected soil chemical properties of different land-use systems

Forest Land-use Systems	Exch. Na (cmol(+)/kg soil)	Exch. K (cmol(+)/kg soil)	Exch. Ca (cmol(+)/kg soil)	Exch. Mg (cmol(+)/kg soil)	BS (%)
Natural forest	0.39[b]	3.60[a]	17.13[a]	5.37[a]	77.94[a]
Eucalyptus globulus	0.60[a]	1.97[b]	11.25[c]	3.58[b]	70.91[a]
Cupressus lusitanica	0.27[d]	2.46[b]	11.59[c]	2.91[b]	80.83[a]
Grevillea robusta	0.34[cb]	2.19[b]	12.56[c]	3.51[b]	79.78[a]
Pinus patula	0.30[cd]	2.45[b]	14.93[ba]	4.75[a]	76.35[a]
LSD	0.09	0.65	2.53	0.98	9.92
CV	24.53	31.78	21.27	28.94	14.53
SIGN	0.0001***	0.0001***	0.0001***	0.0001***	ns

Means within a column followed by the same letter are not significantly different at $p < 0.05$; *** = very highly significant; ** = highly significant; * = significant; ns = non-significant

The highest concentration of exchangeable cations of Ca, Mg, and K, were recorded in the natural forest than plantation forest These are probably attributed to the higher accumulation of soil organic matter (SOM) by adding woody plant litters and understory herbaceous plant residues to soils from different heterogeneity plant species with a high rate of biomass production and those undergoing decompositions, thereby, liberating cations nutrients of Ca, Mg, and K to the soils. The main exchangeable cations (positively charged ions) in soils are calcium, magnesium, potassium, and sodium, which are held or stuck in the soil by organic matter and clay minerals of mostly negatively charged ions, to prevent them from leaching out by water. These explanations are supported by the positive correlation between the organic carbon and exchangeable cations in the soils K (r = 0.576), Ca (r = 0.677), and Mg (r = 0.426). The outcomes of this research were matched with those of Michelsen et al. (1993) and Tellen and Yerima (2018). Similarly, Nsabimana et al. (2008) also observed a higher concentration of exchangeable cations of Ca and Mg in Mixed native species (MNS) forests than in other plantations of mono-exotic tree species in southern Rwanda. However, the minimum mean value of exchangeable Mg was recorded in the *Cupressus lusitanica* plantation (2.91 cmol (+)/kg soil). This is probably due to the lower addition of organic matter to soils from external factors, and the lower exchangeable Mg content of litter to liberate this cation.

The highest concentration of the exchangeable Na+ in *Eucalyptus globulus* plantation might be attributed to the effects of high soil compaction that results in high bulk density, and lower soil moisture content could be facilitated by the soluble salts accumulating in the upper soils rather than being leached down. Similar observations were reported by Michelsen et al. (1993) and Michelsen et al. (1996), that the higher exchangeable sodium under *Cupressus lusitanica, Eucalyptus globulus, Eucalyptus grandis, and Eucalyptus saligna* plantations in the highland of Ethiopia. Among the forest land-use systems, the highest mean value of percent base saturation (80.83) was observed in the *Cupressus lusitanica* plantation. This is probably due to the amount and nature of clay particle contents, low concentration of CEC, and low pH level in soils could have contributed to the existence of higher percent base saturation (PBS) under *Cupressus lusitanica* plantation forest than in other forest land-use systems. The quantity and kind of clay minerals are key elements influencing CEC, as both clay and colloidal organic matter (COM) play a role. These reasons are supported by a significant negative correlation between the soil's PBS and clay (r = -0.202), between PBS and CEC (r = -0.300), and between PBS and pH (r = -0.050). Similarly, Fassil and Charles (2009) suggested that clay and colloidal organic matter are negatively charged and can act as anions; as a result, these two materials can absorb and hold positively charged ions (cations). These findings are consistent with a similar study report by Nsabimana et al. (2008), who had reported a higher percent base saturation (93.7%) under *Cupressus lusitanica* plantation among other plantation forests in southern Rwanda.

The lowest mean value of percent base saturation (70.912) was recorded in the *Eucalyptus globulus* plantation. This is probably due to the lower addition of organic matter that undergoes decomposition and liberates cationic nutrients of Na, K, Ca, and Mg to soils. Additionally, the higher concentration of pH in soils under *Eucalyptus globulus* plantation forests might also contribute to the lower percent base saturation as compared with other forest land use systems. This explanation is supported by the positive correlation between percent base saturation and organic carbon (r = 0.262), and a negative correlation between PBS and pH (r = -0.050). The variation of the percent base saturation (PBS) means values among different forest land-use systems may be due to the variation of the nature of organic matter, amount, and degree of decomposition required to release cation nutrients into soils. Similar observations were reported by Mulugeta et al. (2004), Nsabimana et al. (2008), and Lalisa et al. (2010), as different percent base saturation (%BS) levels under different land-use systems.

4. Conclusion

Exotic tree species plantation forests markedly modify soil physico-chemical properties compared with adjacent natural forests, frequently resulting in reduced soil fertility and structural quality. These differences are mainly associated with species-specific variations in nutrient uptake, biomass production, litter input, nutrient cycling, and water use. Under similar climatic conditions, natural forests generally maintain more favorable soil physico-chemical conditions due to diverse vegetation, balanced litter decomposition, and complex root systems. Among exotic species, *Eucalyptus globulus*, *Cupressus lusitanica*, *Grevillea robusta*, and *Pinus patula* exert differing effects, with *Eucalyptus globulus* showing the most pronounced soil degradation. Consequently, integrated soil management, controlled expansion of *Eucalyptus globulus*, and promotion of sustainable land-use practices are crucial for maintaining soil quality.

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Competing interests

The authors declare that they have no rivalry

Availability of data and materials

The data can be made available upon request.

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