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Research Article

Effect of *Eucalyptus globulus* Plantations on Soil Physicochemical Properties in the Upper Blue Nile, Ethiopia

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In recent years, there has been a substantial conversion of croplands and grasslands to short rotation *Eucalyptus globulus* plantations in the northern highlands of Ethiopia. This has raised concerns among researchers, policymakers, and environmentalists regarding potential adverse effects on soil fertility. To address these concerns, a study was conducted to evaluate the impact of *Eucalyptus globulus* plantations on selected soil physicochemical properties in the region. The study involved four land-use types, comprising two age groups of *Eucalyptus globulus* plantations (4-year-old and 9-year-old), as well as areas designated for grasslands and croplands. Soil sampling was carried out in 10 m × 10 m subplots within each experimental plot, and standard methods were employed for soil analysis. The soil laboratory results were statistically analyzed using Two-way ANOVA and Pearson's correlation coefficients in R software version 4.1.0. The findings revealed significant variations ($p < 0.05$) in soil bulk density, soil organic carbon, and soil pH between the 4-year-old and 9-year-old *Eucalyptus globulus* plantations and the grasslands. A notable difference ($p < 0.05$) in exchangeable acidity was observed between the 4-year-old and 9-year-old E. globulus plantations, with the latter exhibiting the highest mean exchangeable acidity (6.20 ± 0.76). However, no significant differences ($p < 0.05$) were observed between the Eucalyptus plantations and the grasslands in available phosphorus (Av.P), exchangeable calcium (Ca^{2+}), sodium (Na^{+}), and magnesium (Mg^{2+}) concentrations, as well as cation exchange capacity (CEC). The study results has, therefore, implied that *Eucalyptus globulus* plantations induced changes in specific soil properties with varying stand ages in the study area. Nonetheless, it was emphasized that further long-term research is necessary to comprehend the effects of these plantations on soil properties.

1. Introduction

Eucalyptus is one of the fast-growing tree species [1], with an estimated global coverage of 23 million hectares (ha) [2, 3]. In the tropics, the species gained widespread acceptance after the end of the 19th century, mainly because of the commercial importance in various industries such as pulp and paper, charcoal, firewood, timber, and furniture production [4, 5]. In Ethiopia, a plantation program with exotic Eucalyptus trees was launched in the 1890s around the capital city of Addis Ababa [6]. The program was initiated to address the growing demand for fuelwood and timber in urban and preurban communities in the country [7]. Since then, eucalypts have expanded across a considerable portion of Ethiopia [8, 9].

In the northern highlands of Ethiopia, Eucalyptus has become the most preferred tree species in the community and household woodlots because of its rapid growth, coppicing ability, ease of management, and unpalatability to animals [10]. Furthermore, the species offers advantages for land tenure security as it does not require farmers to engage in active cultivation of annual crops, demonstrating productive land use. Consequently, Eucalyptus is now planted on marginal lands as well as fertile plots that were previously devoted to annual food crops [10–12]. Hence, in the past four decades, Eucalyptus has expanded at a dramatic rate in the highlands of Ethiopia [13, 14]. Many concerns have been raised regarding the detrimental effects of Eucalyptus plantations on the environment. Some concerns were related to the adverse impact of the species on soil fertility [15, 16], the understory environment [17, 18], allelopathy [19–22], and underground water and infiltration [23]. Despite these concerns, local farmers in the study area express a strong interest in continuing eucalyptus plantations. According to Bazzana et al. [24], once farmers opt for cultivating Eucalyptus on their farmland, it becomes unlikely for them to revert to growing food crops later on.

The soil physicochemical properties were significantly influenced by monoculture of Eucalyptus plantations. Several studies have shown that it affects bulk density (BD) and particle-size distribution [15], soil organic matter [25], soil pH, and exchangeable cations [26–29]. Mendham et al. [30] and Lugo et al. [31] discovered that Eucalyptus plantations impact the redistribution of macronutrients by absorbing nutrients from the soils into biomass. This leads to the depletion of cations such as calcium (Ca), magnesium (Mg), and potassium (K) [32] when the biomass is harvested and removed. Furthermore, the redistribution of base cations from the soil to the biomass acidifies the surface soil [33].

However, the effects of Eucalyptus plantations on soil quality differ depending on the species [31, 34, 35] and stand age [32, 36]. Aweto and Moleele [37] and Lugo et al. [31] found variations in growth rates, nutrient uptake, and initial soil and substrate conditions among different species, while Binkley et al. [36] and Zhang et al. [32] observed differences in soil quality based on stand age. Therefore, this study aims to examine the impact of a single species, *Eucalyptus globulus*, and two stand age groups on major soil quality indicators.

In recent decades, the northern highlands of Ethiopia, including the study area, have experienced a major shift in land use. Croplands and grazing lands have been converted into monoculture Eucalyptus plantations [12, 38], particularly *Eucalyptus globulus* (*E. globulus*). These plantations have become a preferred species and conspicuous feature of the study area, providing a valuable source of fuel wood and construction materials. They offer significant economic returns and are less susceptible to failure compared to most traditionally cultivated field crops [39–41].

Despite the multitude of benefits of the species, concerns have been growing among policymakers and researchers regarding the adverse impacts of the plantations on soil fertility in the highland of Ethiopia [38, 41–43]. However, Mengistu et al. [13] demonstrated that the fast-growing Eucalyptus species can have positive impacts on organic carbon and total nitrogen in degraded farmlands in the highland of Ethiopia. Further, studies by Yitaferu et al. [44] and Jaleta Negasa [45] found no significant impact of Eucalyptus plantations on the soil physicochemical properties in the central and northern highlands of Ethiopia.

Although some studies have been undertaken on the effect of Eucalyptus plantations on soil quality in the northern highlands of Ethiopia, the findings are diverse and subject to arguments [42, 46, 47]. This lack of clear-cut quantitative evidence makes it difficult for decision-makers and local governors to take appropriate measures for the continued expansion of *E. globulus* plantations on farmlands, grazing lands, and communal lands in the region. This implies that further investigation is necessary to address the existing knowledge gap and offer scientific studies on the impact of this species on soil quality parameters. This study, therefore, aimed to examine the effect of *E. globulus* plantations on soil physicochemical properties in the study area and assess whether the quality of the soil differs with the age of the plantations.

2. Materials and Methods

2.1. Description of the Study Area. The study area, Chirawenz watershed, is located in Sinan District, Ethiopia, between 10°25′00″ and 10°32′30″ North and 37°42′30″ and 37°47′30″ East (Figure 1). It has an altitude ranging between 2430 and 2832 m above sea level (Figure 1). The study area covers a total area of 4665 ha and is situated in the upper Blue Nile Basin.

The study area is characterized by cool subhumid (Weina Dega) agroclimatic zones [48] with a unimodal rainfall pattern. The total annual rainfall ranges from 840 to 1266 millimeters (mm) [49]. The average annual air temperature is 16.6°C, with a mean maximum of 25.8°C and a minimum of 11.3°C [48].

In the study area, subsistence agriculture, practiced by independent farmers on small plots with an average of 0.5 hectares, accounts for 95% of the community's livelihood and is characterized by mixed farming systems [50]. The dominant crops grown include wheat (*Triticumaestivum*), teff (*Eragrostis teff*), maize (*Zea mays*), barley (*Hordeum vulgarae*), sorghum (*Sorghum bicolor*), and potatoes. The dominant soil type of the area is Alisols, which is volcanic in origin and derived from Mio-Pliocene shield volcano lavas [51].

In the study area, *Eucalyptus globulus*, *Juniperus procera*, *Erica arborea*, *Hagenia abyssinica*, *Hypericum revolutum*, and *Olea europae* are the most common plant trees and shrubs [50]. Among the major tree species, *Eucalyptus globulus* has grown extensively in the study area at the expense of croplands and grazing lands. Hence, there has been a major shift in the land-use system of the area.

2.2. Experimental Design. A field survey was carried out in the study area in March 2021 to identify representative sampling sites that meet our objective of examining the impact of *Eucalyptus* plantations on soil properties. Hence, soil samples were collected from four different land-use types that are adjacent to each other. The land-use types considered were grasslands, croplands, and 4-and 9-year-s-old Eucalyptus plantations. The eucalyptus plantation's stand ages of 4 and 9 were selected because the dominant plantations within the study watershed were in these two age groups, allowing for at least four replications. Grasslands were chosen as the control treatment since the current plantations at the study site were mainly converted from grasslands. Therefore, four land-use types that shared similar biophysical conditions, such as agroclimatic zone, soil, and slope, were selected.

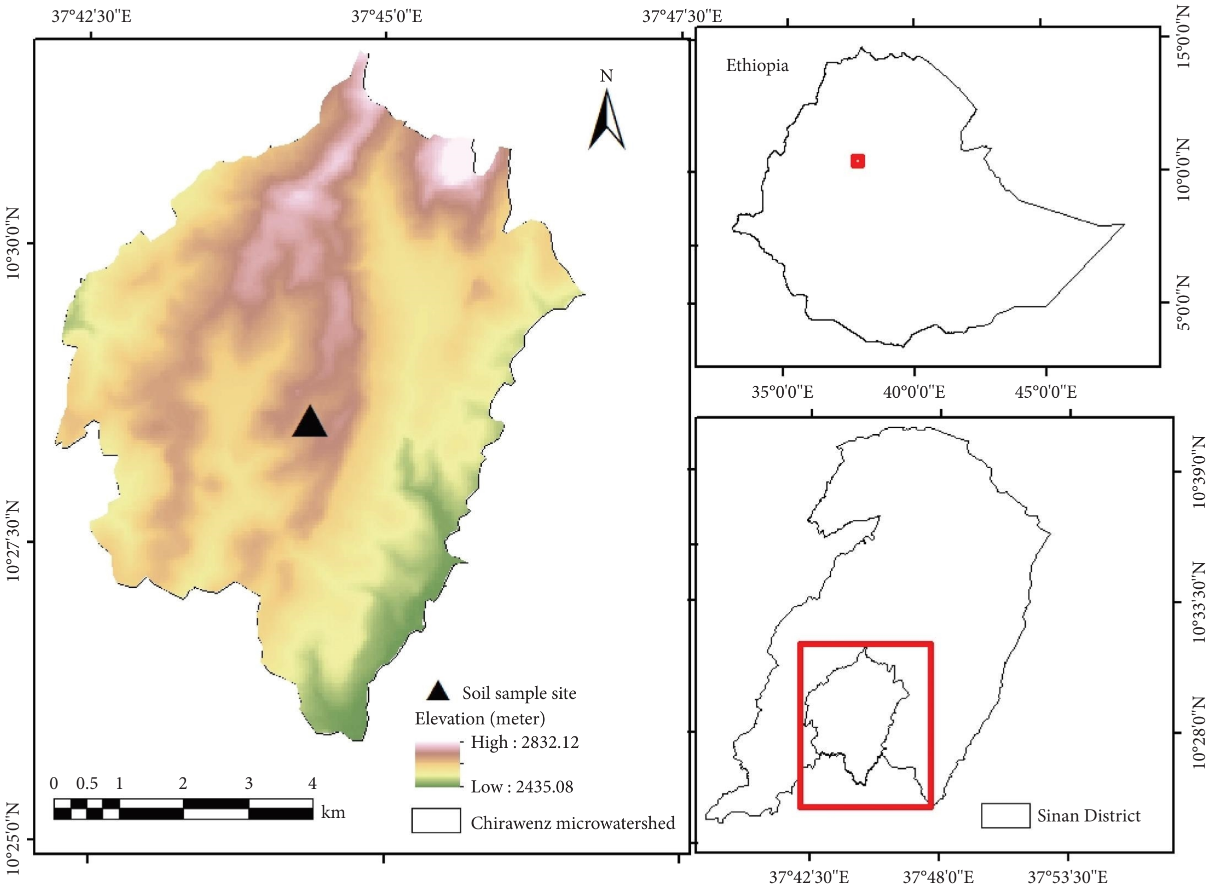


Figure 1: Map of the study area.

2.2.1. *Soil Sampling and Collection.* Each land-use type was divided into four subplots of 10 m × 10 m for soil sampling. The soil samples from the Eucalyptus plantations and the other land uses were collected from the four corners and center of each layout using the "X-layout" design, and an attempt has been made to avoid sampling too close to the borders of different land uses to minimize the potential influence of the adjacent land use. Composite samples were taken from the four corners and center of each layout at two soil depths (0–20 cm and 20–40 cm) for each subplot from each land-use type using a soil auger. One kilogram (kg) of composited soil sample was collected from each location, properly labeled, and packed in plastic bags before transportation to the laboratory. A total of 32 composite soil samples (four land uses × four replications × two depths) were collected for laboratory analyses. Furthermore, 32 undisturbed soil samples (at depths of 0–20 cm and 20–40 cm) were collected independently from each subplot of the land-use types using a core sampler of height 5 cm and diameter 5 cm for bulk density determination.

2.2.2. *Soil Laboratory Analysis.* The collected soil samples were analyzed at Deber Birhan Agricultural Research Center Soil and Water Laboratory, North Shewa, Ethiopia. The soil sample was analyzed following the standard procedures outlined by Van Reeuwijk [52].

Bulk density (BD) was determined using a core sampler of a known volume following the procedures of Blake [53]. The soil bulk density was determined using the core method for undisturbed soils, where the core soil sample was oven-dried at 105°C for 24 h [54]. Soil texture analysis was performed using the Bouyoucos hydrometer method, [55]. Soil pH was determined using $a1:2.5$ (w/v) soil-to-water solution ratio using a digital pH meter [56, 57]. Soil organic carbon (OC) was determined using the Walkley and Black [58] method, and total nitrogen (TN) was determined by wet oxidation using the Kjeldahl digestion, distillation, and titration method [59]. The available phosphorus (av. P) content of the soil was determined by the Olsen method using 0.5 M sodium bicarbonate as the extracting solution [60]. Exchangeable bases (Ca^{2+}, K^+, Mg^{2+}, and Na^+) were established using the ammonium acetate extraction method. The concentrations of Ca and Mg were determined using atomic absorption spectrophotometry, whereas K and Na were assessed using a flame photometer [61]. Exchangeable acidity (H^+ and Al^{3+}) was determined in 1 M KCl extracts titrated with 0.01 M NaOH [62]. The cation exchange capacity (CEC) was obtained by adding all exchangeable cations, as described by Tan [63].

2.3. Statistical Analysis. The soil laboratory results were checked for normality before analysis. Analysis of variance was employed in the open-source software R version 4.1.0 to look for the variation in the means of the selected soil physicochemical properties across land uses and soil depths. When the analysis of variance showed a significant difference ($p < 0.05$) among the land uses and soil depths for each soil quality indicator, a mean separation for each was made using Tukey's HSD test for pairwise comparisons. Pearson's correlation coefficients were used to assess the significance of the relationships between the selected soil quality indicators.

3. Results

3.1. Physical Soil Properties. Table 1 presents the results of the analysis of variance on selected physical properties of soil. The analysis showed significant differences ($p < 0.001$) in soil bulk density across different land-use types. Cropland had the highest soil bulk density (BD) (1.49 ± 0.04) in the upper soil layer (0–20), followed by the 4-year-old *E. globulus* plantations (1.47 ± 0.04). The 9-year-old *E. globulus* plantations (1.25 ± 0.03) and grassland (1.26 ± 0.04) had lower soil bulk density.

Regarding the soil textural fractions, the proportions of sand ($p < 0.01$), clay ($p < 0.05$) and silt ($p < 0.05$) significantly differed across the land-uses types, with clay fraction also differing significantly ($p < 0.05$) between the soil depths (0–20 cm and 20–40 cm). Further, the silt fraction was higher in the grassland (25.0 ± 1.00), followed by *E. globulus* plantations in the upper soil layer. The sand fraction was higher in croplands (22.5%) than the other land-use types. On the other hand, the proportion of clay was higher in both age groups of *E. globulus* plantations (65%) as compared to the grassland and cropland in both soil depths. The soil analysis revealed that the dominant soil textural class was clay across all land uses in both 0–20 cm and 20–40 cm soil depths.

3.2. Chemical Properties of the Soil. The analysis of variance indicated significant differences ($p < 0.05$) in soil pH (H_2O), soil organic carbon (OC), and total nitrogen (TN) across land-use types (Table 2). In addition, total nitrogen differed significantly ($p < 0.05$) between soil depths (0–20 cm and 20–40 cm). The interaction effect of land use and soil depth revealed significant differences ($p < 0.05$) in OC and TN.

Soil pH (H_2O) in the four land uses ranged from 4.76 to 5.42, classified as strong acidic soil (Table 2). There was a significant difference ($p < 0.05$) in the soil pH across land uses at both0–20 cm and 20–40 cm soil depths. The mean soil pH was higher in the grasslands (5.35 ± 0.02) and lower in 9-year-old Eucalyptus plantations (4.85 ± 0.25).

The soil organic carbon (OC) was higher in the grasslands (2.62 ± 0.26) and lower in the croplands (1.06 ± 0.28) in the upper soil layer (Table 2). The soil organic carbon was significantly different ($p < 0.01$) across the land uses at the upper soil depth (0–20 cm). As the Pearson coefficient of correlation is shown (Figure 2), there was a significant correlation between soil OC and BD in the upper layer of the soil depth ($r = -0.54$; $p < 0.05$). The soil organic carbon of the 9-year-old plantation was higher than the 4-year-old *E. globulus* at both 0–20 cm and 20–40 cm soil depths. Except for cropland, the soil organic carbon decreased with increasing soil depth in all three land uses.

There was a significant difference ($p < 0.001$) in the total nitrogen (TN) content among the grasslands, croplands, and 4- and 9-year-old *E. globulus* plantations in the upper soil layer (Table 2). Grasslands had the highest TN (0.28 ± 0.03), while croplands had the lowest TN in both 0–20 cm and 20–40 cm soil depth. The ratio of OC: TN did not differ significantly ($p > 0.05$) across the land-use types; however, the ratio of OC: TN was higher in both age groups of the *E. globulus* plantations in the upper soil layer. The results of Pearson correlation coefficients indicated that total nitrogen and organic carbon had a strong significant positive relationship ($r = 0.98$; $p < 0.01$) in the upper layer of soil depth across the land uses (Figure 3).

The available phosphorus (Av. P) ranged from 8.92 to 7.27, indicating a low-level range class. Its concentration did not vary significantly ($p > 0.05$) across the 0–20 cm and 20–40 cm soil depths.

The overall analysis of variance (Table 3) showed significant differences ($p < 0.01$) in cation exchange capacity (CEC) and exchangeable acidity (Ex. Acidity). The results of the interaction of land use and soil depth also revealed that CEC and exchangeable calcium (Ca^{++}) significantly differed ($p < 0.05$). Among the exchangeable cations, only potassium (K^+) exhibited a significant difference ($p < 0.05$) among the land uses in the upper soil layer with the grasslands having the highest exchangeable K^+ concentrations (0.75 ± 0.04) (Figure 4).

The base saturation (BS) did not vary significantly across the land uses in both layers of soil depths (Table 3). However, the mean base saturation was higher (68.43) in grassland and lower in 9-year-old *E. globulus* plantations (55.87). The Pearson correlation coefficient (Figure 5) revealed that there was a significant correlation between base saturation and soil pH (H_2O) in both soil depths of, 0–20 cm ($r = 52$; $p < 0.05$) and 20–40 cm ($r = 0.63$; $p < 0.01$).

On the other hand, the exchangeable acidity (H^+ and Al^+) was significantly different ($p < 0.001$) in both layers of the land-use types (Figure 6). The pairwise comparison indicated a significant difference ($p < 0.05$) in exchangeable acidity among the 4- and 9-year-old *E. globulus* plantations at both soil depths.

The 9-year-old *E. globulus* plantation had the highest mean exchangeable acidity (6.20 ± 0.76), followed by the 4-year-old Eucalyptus plantation (1.17 ± 0.29) at the upper soil depth. The Pearson correlation coefficient (Figure 7) revealed strong negative correlation between exchangeable acidity and base saturation at both soil depths, 0–20 cm ($r = 86$; $p < 0.01$) and 20–40 cm ($r = 0.89$; $p < 0.01$).

4. Discussion

4.1. The Effect of Land-Use Change on the Physical Properties of the Soil. When land is converted from its natural state, there are several changes in the soil's physical characteristics,

Table 1: Mean (±SE) of selected soil physical properties in the 0–20 and 20–40 cm soil depths for different land uses. The data also include the overall analysis of variance.

Soil quality indicators	Depth	Land uses			
		Grasslands	Croplands	4-year-old *E. globulus*	9-year-old *E. globulus*
Bulk density (g·cm^{-3})	0–20 cm	1.29 (±0.04)^{ab}	1.50 (±0.10)^{a}	1.42 (±0.04)^{ab}	1.21(±0.03)^{b}
	20–40 cm	1.23 (±0.05)^{b}	1.48(±0.20)^{ab}	1.53 (±0.09)^{a}	1.30 (±0.03)^{ab}
Sand (%)	0–20 cm	17.0 (±2.38)^{ab}	22.5 (±2.62)^{a}	14.0 (±1.41)^{b}	13.5 (±1.25)^{b}
	20–40 cm	12.5 (±3.09)^{a}	17.5 (±2.62)^{a}	15.0 (±3.10)^{a}	9.5 (±1.50)^{a}
Clay (%)	0–20 cm	58.0 (±2.94)^{a}	59.5 (±2.36)^{a}	65.0 (±2.08)^{a}	65.0 (±0.57)^{a}
	20–40 cm	64.0(±2.44)^{a}	63.5(±2.06)^{a}	65.5(±3.59)^{a}	72.0 (±0.81)^{a}
Silt (%)	0–20 cm	25.0 (±1.00)^{a}	18.0 (±1.41)^{b}	21.0 (±1.91)^{ab}	21.5 (±0.95)^{ab}
	20–40 cm	23.5 (±2.21)^{a}	19.0 (±1.73)^{a}	19.5 (±0.50)^{a}	18.5 (±0.95)^{a}

Overall analysis of variance

	Land use	Soil depth	Land use * soil depth
Bulk density (g cm^{-3})	***	NS	NS
Sand (%)	*	NS	NS
Clay (%)	*	*	NS
Silt (%)	**	NS	NS

The mean values followed by the different superscripts across a row in different letters represent that they are significantly different at $p \le 0.05$; *, **, and *** mean significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$ levels, respectively, and NS means nonsignificant differences.

including bulk density and soil texture. In our investigation, the impact of land-use change revealed a significant difference in soil bulk density. The croplands had a greater (47.28%) mean soil bulk density (BD) than grasslands, and the 4-year-old *E. globulus* plantations in the upper soil layer came in second (14%). Both the 9-year-old *E. globulus* plantations and the grassland had lower BD. Therefore, the change in soil BD in the upper soil layer across different land-use patterns may be caused by the amount of soil organic carbon and compaction. The higher soil BD in croplands may be associated with low soil organic carbon, as well as increased soil disturbance and compaction from repeated cultivation [64, 65]. Further, our soil analysis result showed that the soil bulk density increased with soil depth due to more compaction by overlying surface soil and lower soil organic matter in the subsurface layer [66]. Compaction reduces pore space and affects the soil's ability to absorb water and nutrients.

Although soil texture is considered to be the most static physical property of soil [67, 68], the indirect impact of land-use practices could have been viewed as affecting the overall texture. For example, improper land management, such as deforestation, overgrazing, and inappropriate agricultural practices, can lead to soil erosion, resulting in the depletion of topsoil containing finer particles like clay. The results of our study indicated that there was a significant difference ($p < 0.05$) in silt and sand soil textural fractions between the Eucalyptus plantations and grasslands. There was a higher proportion of sand in croplands (32.35%) as compared to grasslands. This might be related to frequent tillage practices, which allowed fine soil particles to be transported, leaving a coarse soil fraction. According to Feeney et al. [69], intensive farming practices can lead to the loss of topsoil and result in increased sand content, while vegetation cover promotes the accumulation of fine particles, such as silt and clay.

On the other hand, the clay content was 6.96% and 12.29% higher in 4 -year-old and 9-year-old *E. globulus* plantations than in the grasslands, respectively. The higher clay content in Eucalyptus forests compared to croplands can be attributed to litter accumulation [70, 71], root systems [72], soil erosion prevention [10, 73], and altered microclimate [74]. Eucalyptus forests produce a significant amount of litter over time and decompose and accumulate organic matter in the forest floor results in increased clay content in the topsoil [70]. The roots of Eucalyptus trees are extensive and can penetrate and breakdown rocks and soil particles contributing to the accumulation of clay [75]. Additionally, the roots of Eucalyptus trees release organic acids that enhance the weathering of minerals and the release of clay particles [76]. Eucalyptus forests often act as natural barriers against soil erosion [71]. The dense network of roots and leaf litter layer help stabilize the soil and reduce the impact of water runoff. This protective layer prevents the loss of fine clay particles from being lost, allowing them to accumulate within the forest area. Furthermore, Eucalyptus forests can create a microclimate [77] with higher humidity and lower temperature compared to croplands, which favor the breakdown of organic layers through the processes, such as hydrolysis and weathering. Similarly, Aweto and Moleele [37] observed comparable findings. The continuous monoculture of cereal crops without proper soil management practices in the study area contributed to nutrient depletion and soil erosion in the study watershed, where the removal of topsoil including clay particles may reduce clay content in croplands. In addition, soil analysis results revealed that the percentage of clay fraction increased

Table 2: Mean (±SE) of selected soil chemical properties in the 0–20 and 20–40 cm soil depths across land uses.

Soil quality indicator	Depth	Land uses			
		Grasslands	Croplands	4-years-old *E. globulus*	9-years-old *E. globulus*
pH (H_2O)	0–20 cm	5.42 (±0.11)^{ab}	5.29 (±0.21)^{ab}	5.24 (±0.11)^{a}	4.76 (±0.09)^{b}
	20–40 cm	5.28 (±0.11)^{ab}	5.26 (±0.25)^{ab}	5.30 (±0.04)^{a}	4.95 (±0.18)^{b}
Organic carbon (%)	0–20 cm	2.62 (±0.26)^{a}	0.09 (±0.02)^{b}	1.09 (±0.22)^{b}	1.90 (±0.15)^{ab}
	20–40 cm	1.49 (±0.13)^{a}	0.13 (±0.03)^{a}	1.04 (±0.16)^{a}	1.50 (±0.13)^{a}
Total N (%)	0–20 cm	0.28 (±0.03)^{a}	0.09 (±0.02)^{b}	0.10 (±0.01)^{b}	0.17 (±0.02)^{b}
	20–40 cm	0.12 (±0.00)^{a}	0.13 (±0.03)^{a}	0.10 (±0.01)^{a}	0.14 (±0.01)^{a}
Soil available P ($mg{\cdot}kg^{-1}$)	0–20 cm	7.27 (±0.44)^{a}	8.46 (±0.68)^{a}	8.92 (±0.00)^{a}	7.49 (±0.72)^{a}
	20–40 cm	8.36 (±0.98)^{a}	7.53 (±1.07)^{a}	8.34 (±0.68)^{a}	8.91 (±1.37)^{a}
SOC : TN	0–20 cm	9.29 (±0.25)^{a}	8.46 (±0.65)^{a}	10.14 (±0.77)^{a}	11.11 (±0.68)^{a}
	20–40 cm	12.30 (±1.15)^{a}	11.07 (±0.81)^{a}	10.08 (±0.34)^{a}	10.67 (±0.40)^{a}

	Overall analysis of variance		
	Land use	Soil depth	Land use × soil depth
pH (H_2O)	*	*	NS
Organic carbon (%)	**	NS	*
Total N (%)	*	*	*
Soil available P ($mg{\cdot}kg^{-1}$)	NS	NS	NS
SOC : TN	NS	NS	NS

The mean values followed by the different superscripts across a row in different letters represent that they are significantly different at $p \leq 0.05$; *, **, and *** mean significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$ levels, respectively, and NS means nonsignificant differences.

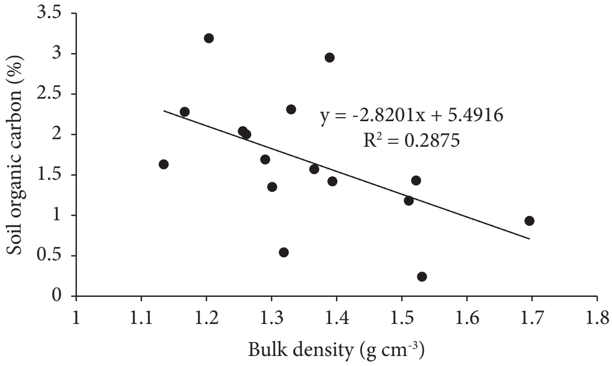


Figure 2: The correlation between organic carbon and bulk density in the upper soil layer.

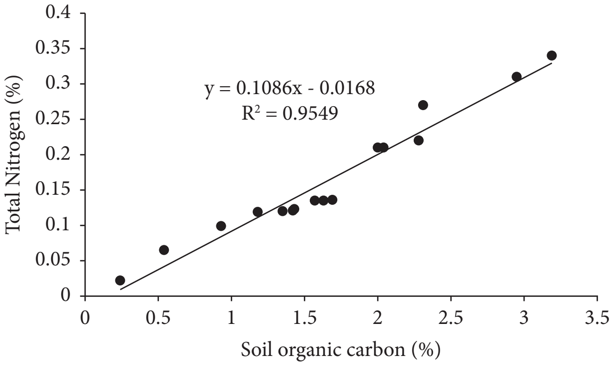


Figure 3: The correlation between soil organic carbon and total nitrogen in the upper soil layer.

Table 3: The overall analysis of variance of selected soil chemical properties across the land uses.

Exchangeable cation (c·mol·kg^{-1})	Overall analysis of variance Land use	 Soil depth	 Land use × soil depth
Potassium	NS	NS	NS
Calcium	NS	NS	*
Magnesium	NS	NS	NS
Sodium	NS	NS	NS
Ex. acidity	***	NS	NS
Cation exchange capacity	**	NS	*
BS (%)	NS	NS	NS

*, **, and *** mean significant differences at $p < 0.05$, $p < 0.01$, and $p < 0.001$ levels, respectively, and NS means nonsignificant differences.

significantly ($p < 0.05$) with increasing soil depth across land uses. This might be due to the translocation of clay from the upper layer to the lower layer [78, 79].

4.2. The Effect of Land-Use Change on the Chemical Properties of the Soil. Soil pH is one of the "master soil variables" that influence the biological, chemical, and physical properties of the soil [80] and is subjected to change by anthropogenic interventions [81, 82]. The pairwise comparison of soil pH revealed that there was significant variation ($p < 0.05$) between 4- and 9-year-old *E. globulus* plantations in both soil layers. Further, the results showed that the mean soil pH in the 9-year-old *E. globulus* plantation was 9.25% lower than in grassland. Eucalyptus trees are known to release certain organic acids into the soil through their root systems and fallen leaves [83]. These organic acids can contribute to soil acidification, potentially lowering the pH of the soil. Further, the lower soil pH in the Eucalyptus plantation could be associated with the depletion of the soil base cations with higher growth rates of the species [30, 38]. As Eucalyptus trees grow, they efficiently take up nutrients from the soil [37], which can lead to base cation depletion in the immediate vicinity, resulting in lower soil pH.

The concentrations of soil organic carbon (SOC) and total nitrogen (TN) differed significantly among the land-use types in the upper layer of the soil depth. The SOC was significantly higher in the grasslands (2.62 ± 0.26) and followed by the 9-year-old *E. globulus* plantation (1.90 ± 0.15) in the upper soil layer. Similar results were reported by Temesgen et al. [38] and Bardgett et al. [84], who found that

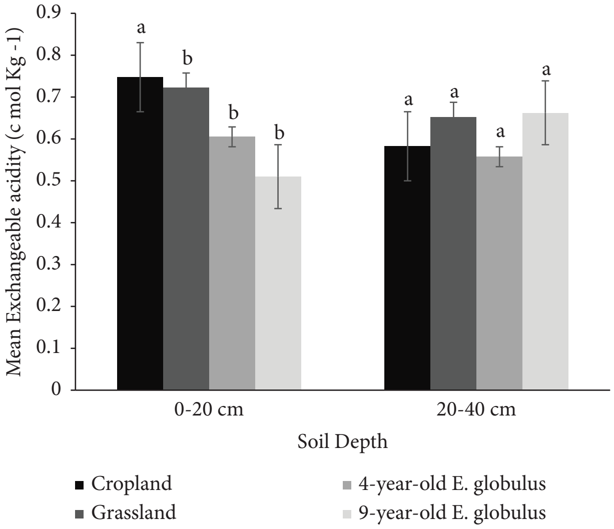
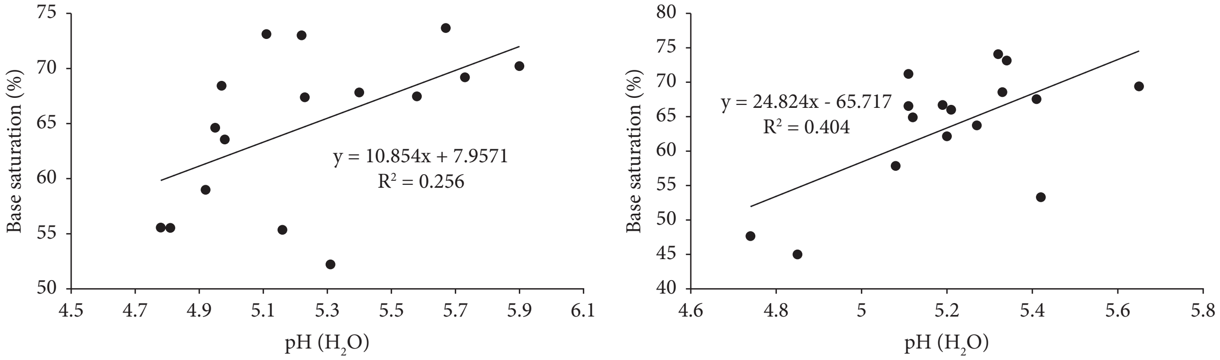


Figure 4: Mean exchangeable potassium in the 0–20 and 20–40 cm soil depths across the land use.



(a)

(b)

Figure 5: Pearson correlation between soil pH (H_2O) and base saturation in the upper soil layer (a) and lower soil layer (b).

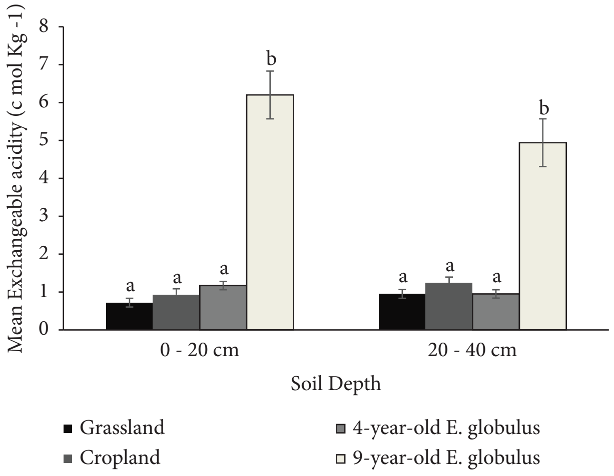
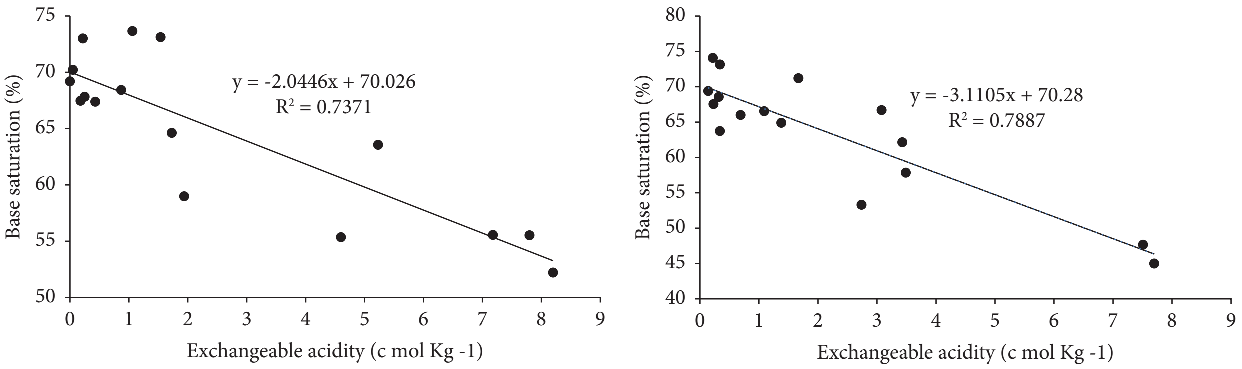


Figure 6: Mean exchangeable acidity in the 0–20 and 20–40 cm soil depths across the land uses.

although grazed grasslands contain little plant thatch, higher concentrations of SOC were recorded in grasslands. The lowest concentrations of organic carbon were recorded in the croplands. Frequent tillage practices and the removal of crop residues from farmlands might be the possible causes of low OC in croplands in the study area [85, 86].



(a) (b)

FIGURE 7: Pearson correlation between exchangeable acidity and base saturation in the upper soil layer (a) and lower soil layer (b).

Further, the soil OC of the 9-year-old *E. globulus* plantation was 74.31% and 44.23% higher than the 4-year-old *E. globulus* at both 0–20 cm and 20–40 cm soil depths, respectively. This is because as the age of the Eucalyptus plantation increases, accumulation of litter increases, and the development of roots, and the relatively lower growth rate of the trees enrich the soil by increasing organic carbon [25, 27, 87–89].

On the other hand, the concentration of total nitrogen was 64.29% and 39.29% lower in 4-year- and 9-year-old *E. globulus* plantations as compared to grasslands, respectively. Because Eucalyptus litter has a higher level of lignin and soluble polyphenols than pasture species' litter [89, 90], it decomposes more slowly than other types of litter, which may account for the lower concentration of soil TN under *E. globulus* plantations [27, 30]. Further, the results revealed that the ratio of OC: TN was relatively higher in both groups of *E. globulus* plantations which show lower net N mineralization in the Eucalyptus plantations [91].

Regarding the exchangeable cations, the results revealed that the concentration of exchangeable cations (K^+, Ca^{++}, Na^+, and Mg^{++}) fell at a medium rate across land uses [92, 93]. Among the exchangeable cations, K^+ showed significant variation across land-use types. As compared to grassland, the concentration of K^+ was significantly lower by 17% and 29% at 4-year- and 9-year-old *E. globulus* plantations, respectively. However, the other exchangeable cations did not show a significant variation across the land-use types and the soil depths.

Further, the soil analysis demonstrated that the concentration of exchangeable acidity was higher in the two age groups of *E. globulus* plantations than grasslands. The results of the pairwise comparison indicated a significant difference ($p < 0.05$) in exchangeable acidity among the 4- and 9-year-old *E. globulus* plantations in both layers of soil depth. The results of the Pearson correlation coefficient revealed strong negative correlation between exchangeable acidity and base saturation at both soil depths. Therefore, the decreased base saturation and increased exchangeable acidity in the Eucalyptus plantations could be associated with increased cations uptake by the plantations. The consequence of this change may bring a change in the proportions of adsorbed cations in the soil exchange complex and tend to be replaced with a higher proportion of H^+ and Al^{++} ions [38].

5. Conclusion

We found that the conversion of grasslands to different land uses, including *E. globulus* plantations and croplands, resulted in significant alterations in some soil physicochemical properties. Notable findings include higher soil bulk density (BD) in 4-year-old *E. globulus* plantations compared to 9-year-old ones, with increased BD observed with soil depth. Variations in soil pH, soil organic carbon (SOC), total nitrogen, and potassium (K^+) concentrations were identified across land-use types and depths. Older Eucalyptus plantations exhibited lower pH, potentially linked to organic acid release, and higher SOC due to litter accumulation. Total nitrogen concentrations were lower in Eucalyptus plantations and attributed to slow litter decomposition. Decreased K^+ concentration and higher exchangeable acidity in Eucalyptus plantations indicated altered nutrient dynamics. Overall, the study underscores the impact of land-use changes and effect of stand ages of *E. globulus* plantations on specific soil properties. As the stand ages of eucalyptus plantation increase, its effect on the selected soil physicochemical properties varied significantly such as BD, SOC, soil pH, and exchangeable acidity. The findings emphasize the necessity for further research to fully comprehend the effects of *E. globulus* plantations on soil properties, taking into account successive stand ages, management practices, and agroecological zones that were not thoroughly addressed in our study.

Data Availability

Data will be made available on request.

Disclosure

This paper is part of the doctoral study entitled "Modelling *Eucalyptus globulus* Spatial Distribution and Its Effect on the Physical Environment in the Upper Blue Nile Basin, Ethiopia."

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Abdurohman Yimam conceived and designed the study, analyzed and interpreted the data, and wrote the paper. Asnake Mekuriaw, Dessie Assefa, and Woldeamlak Bewket analyzed and interpreted the data and wrote the paper.

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