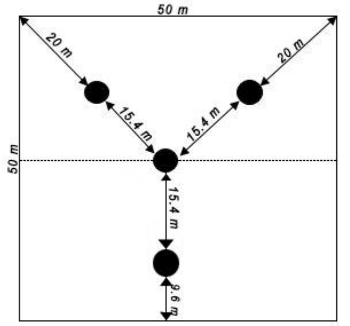

Effects of *Eucalyptus* species on soil physicochemical properties in Ruhande Arboretum, Rwanda

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Abstract

This study combines research on soil physical and chemical properties as affected by four *Eucalyptus* species in Ruhande arboretum. The soil samples for research properties were taken from 0-20 cm depth using auger and one undisturbed core from each sampling unit was taken for the analysis of soil bulk density. Soil bulk density and moisture did not differ significantly between all treatments. Sand proportions differed significantly only between *E. tereticornis* and *E. maidenii* whereas silt and clay were non-significant. The soil under *Eucalyptus* was sandy, with sand proportion ranging from 66.4-71%. Bulk density increased with increasing sand whereas moisture content showed a reverse trend. The soil samples for studying chemical properties were taken as described in Nsabimana et al. 2008. All chemical parameters except base saturation differed significantly between treatments. Soil pH was strongly acidic but rich in total nitrogen and organic carbon which was attributed to higher litter production, its relatively faster rate of decomposition, and greater amount of residues produced by the eucalypts. Carbon/nitrogen ratio, CEC, and BS were high under all treatments while the available phosphorus was lower which was attributed to the low pH. Future studies should test if the species similarly affect the soil or not and confirm if the species increase soil nutrients. Benchmarked study sites should be used to enable differences in the species effects on the site if any.

Keywords

Eucalyptus; Soil; Physicochemical properties; Ruhande Arboretum

Contents

1 Introduction

Eucalyptus is a very large genus indigenous to Australia. A different number of species are reported in this genus. Bekele (2015) reported that the genus Eucalyptus contains more than five hundred species. On the other hand, Biltshire (2004) recorded seven hundred species in the same genus. They have been extensively introduced into other countries because of their fast growth, adaptation to different agroecologies, and the escalating demand for paper and plywood products (Teketay 2003). The genus was introduced to East Africa in the late 19th and early 20th centuries and by the early 1970s, the area of Eucalyptus in Ethiopia, Rwanda, Uganda, Kenya, and Sudan had reached 95,684 ha (FAO 1979). The largest plantations at that time were in Ethiopia and Rwanda, 42,300 ha and 23,000 ha, respectively (Dessie and Erkossa 2011). Eucalyptus plantations in Rwanda covered approximately 12,000 ha in the 1990s (Chalchat et al. 1997). They were introduced to control soil erosion and form a readily renewable source of firewood and building materials which were highly demanded at the time of their introduction (Chalchat et al., 1997). The Arboretum of Ruhande in Rwanda hosts 69 Eucalyptus species (Nsabimana et al. 2008).

The profit derived from Eucalyptus is considerably higher than cultivating crops (Abebe and Tadesse 2014). This is because they are a source of various uses for rural and urban people such as medicinal value (Eucalyptus leaves have been used in the treatment of colds), and a source of income by selling tree biomass such as stem for construction and twigs, leaves and bark for firewood purpose (Abebe and Tadesse 2014). However, the species are reported to have negative environmental impacts such as soil degradation and loss of biodiversity (Laclau et al. 2010), high water uptake rates, soil fertility depletion, disruption of biodiversity conservation, and their allelopathic effects that inhibit undergrowth regeneration (Cortez et al. 2014).

The study by Amsalu (2019) showed that most farmers perceived that *Eucalyptus* trees affect soil properties and crop production through nutrient and moisture competition. The soil on which *Eucalyptus* is planted presents a decrease in its water content and an increase in its bulk density (Ravina, 2012). Zhang et al. (2021) reported that soil texture was among the key factors affecting soil water-holding capacity. They reported a decreased water-holding capacity as a result of an increase in sand content. It is previously reported that *Eucalyptus* species have effects on soil texture. Balamurugan et al. (2000) reported an increase in clay and a decrease in sand content under *Eucalyptus* plantation. However, a study by Amsalu (2019) showed that *Eucalyptus* plantations had a significantly higher effect on soils that increased the sand and lowered the clay contents. These effects result from high nutrient demand by

Eucalyptus (Laclau et al. 2010). This demand leads to the extraction of nutrients from the soil by *Eucalyptus* thus reducing soil quality. Soil quality includes soil physical, chemical, and biological properties, as well as soil processes and their interactions (Andrews and Carroll 2001).

In Rwanda, little research has been done in this field, i.e., scanty information exists about the effects of *Eucalyptus* species on soil properties. Nsabimana et al. (2008) studied soil chemical properties under plots of different species in Ruhande Arboretum. To safeguard and maintain the sustainability of the soil under *Eucalyptus* plantations, it is imperative to evaluate the effects of *Eucalyptus* species on the soil's physical properties, hence the need for this study.

2 Materials and methods

2.1 Study site description

The study was carried out in Ruhande Arboretum in Southern Rwanda (altitude: 1737 m; lat. 2°36´S and long. 29°44´E) (Burren, 1995). The climate in the region is tropical humid, the average annual temperature is 19.6°C and the mean annual precipitation is 1232 mm (Burren 1995). The rainfall has a bimodal pattern: the heavy rainy season extending from March to May and the mild rain from October to December. The two rainfall seasons alternate with two dry seasons, one from January to February and the other from June to September. The soil in the Arboretum is classified as a Ferralsols (FAO 1998), formed from the parent material of schists and granites mixed with mica schist and quartzite (Verdoodt and Ranst 2003).

2.2 Field procedure

To study the effects of different species of *Eucalyptus* on soil physicochemical characteristics, four species in Ruhande Arboretum were used (Table 1). These were selected because we could get enough plots satisfying our experimental design. Soil samples were collected during the rainy season, which extends from March to May. Three plots per species were used as replicates to make 12 plots in total (Table 1). In each plot, four soil samples were collected in a Y-shaped design using an auger at a depth of 0-20 cm of the soil surface. Two samples were collected at 15.4 m from the square plot center toward its edges. One sample was collected from the plot center and one at the midpoint (15.4 m from the plot center) of a straight line connecting the plot center with the plot side that forms a right angle with this line (Figure 1).

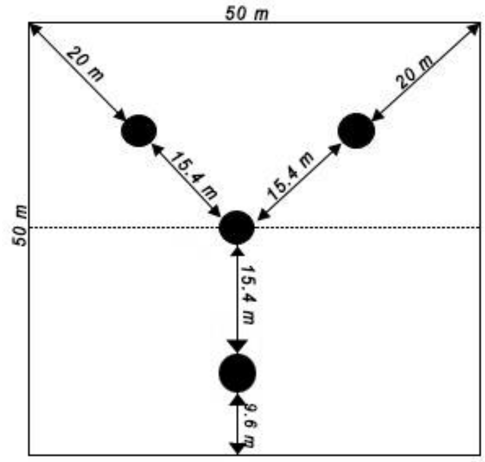

Figure 1. Layout of sampling points as positioned in a particular Eucalyptus species plot in Ruhande Arboretum, Rwanda.

Soil samples were properly labeled to avoid identification errors during transfer. The four sub-samples from each plot were properly mixed to form a single composite sample, and therefore, 12 composite samples were obtained for the analysis of soil physical properties. The fine (wet soil) was used for the determination of moisture content, while the soil for the determination of particle size distribution was initially dried and later ground to pass through a 2 mm sieve for further laboratory analysis. Additionally, separate undisturbed soil core samples were taken with a sharp-edged steel cylinder forced manually into the soil for bulk density determination via oven-drying (Kassa et al. 2019). The experimental plots for the current study are in the middle of the other plots in the Ruhande Arboretum and we couldn't get free land without trees from which to take control samples.

Table 1. Characteristics and geographic locations of studied study plots in Ruhande Arboretum, Rwanda (Source: *Nsabimana et al., 2008*).

Plot No.	Geographical location		Treatments	Year of planting
109	02°36.73 S	29°45.57 E	*Eucalyptus tereticornis*	1943
110	02°36.81 S	29°45.59 E		1945
450	02°37.08 S	29°45.07 E		1949
77	02°36.82 S	29°45.12 E	*Eucalyptus microcorys*	1943
367	02°36.62 S	29°45.19 E		1949
448	02°37.08 S	29°45.05 E		1949
179	02°36.66 S	29°45.61 E	*Eucalyptus maidenii*	1946
377	02°36.59 S	29°45.32 E		1949
452	02°37.07 S	29°45.09 E		1949
20	02°36.89 S	29°45.06 E	*Eucalyptus saligna*	1934
375	02°36.59 S	29°45.32 E		1949
442	02°37.10 S	29°44.96 E		1950

2.3 Laboratory methods

Soil sampling for chemical analysis and soil chemical analysis were described in Nsabimana et al. (2008). Soil samples were sieved (2 mm), dried, and ground before laboratory analysis. The particle size analysis was done with the help of the hydrometer method (Bouyoucos 1962). Bulk density, on the other hand, was determined with the help of the widely known double-cylinder sampler method for the measurement of soil water (Cooper 2016).

2.4 Data analysis

Data processing and analysis for physical properties were done using GenStat software for the analysis of variance (ANOVA), to test if there exists a statistically significant difference of the species in their effect on physical properties.

3 Results and discussion

3.1 Soil particle size distribution (texture)

According to the USDA textural classification, among four tested *Eucalyptus* species, plots of three (*E. microcorys, E. tereticornis, and E. saligna*) showed a sandy clay loam textural class and one (*E. maidenii*) showed a sandy loam textural class at 0-20 cm depth. The textural proportions for the tested *Eucalyptus* species are presented in Table 2. The soils of the sites were predominantly sandy, ranging between 66.4 - 71.3 %. The clay content was small, ranging from 19.3 to 23.6 %.

Table 2. Average textural values observed in soils under Eucalyptus tree species in Ruhande Arboretum with their respective classes. Significant differences in mean values are indicated by different letters, a<ab<b (Tukey test at 5 % significant level).

Species	Sand (%)	Silt (%)	Clay (%)	Textural classes USDA classification
E. maidenii	71.27^{a}	9.400^{a}	19.33^{a}	Sandy Loam
E. microcorys	68.15^{ab}	9.250^{a}	22.60^{a}	Sandy Clay Loam
E. saligna	67.88^{ab}	10.967^{a}	21.15^{a}	Sandy Clay Loam
E. tereticornis	66.40^{b}	10.017^{a}	23.58^{a}	Sandy Clay Loam
F value	**0.091**	**0.308**	**0.248**	

The study showed no significant differences in the total sand, silt, and clay percentages between the soils under different *Eucalyptus* tree species (p>0.05), but a significant difference was recorded for total sand percentage between *E. tereticornis* and *E. maidenii.* This means that the two species affect sand in the soil under them differently. The result was nearly similar to the findings by Alemayhu and Yakob (2020) who detected non-significant differences in the mean proportions of sand, silt, and clay fractions between the soils under *Eucalyptus* species. The non-significant differences in the mean proportions of these fractions between the soils under *Eucalyptus* species suggest that the soils are texturally similar. The observed soil particle size distribution may have been derived from the parent material, which is the same for all test plots, under the same climatic conditions and similar topography. On the other hand, having similar soil behavior may show that the four test species affect the soil similarly. According to Landon (1991), sand and sandy loam soils showed high bulk density values (1.2 to 1.8 g cm^{-3}). Therefore, a high proportion of sand as observed may suggest that there is an increase in soil compaction.

3.2 Bulk density

In this study, the obtained soil bulk density data across *Eucalyptus* species did not show significant differences in the effects on soil bulk density between treatments ($p<0.05$) (Table 3).

Table 3. Average bulk density observed in a study to compare the effect of four Eucalyptus species on soil properties in Ruhande Arboretum, Southern Rwanda.

Species	Bulk density (g cm^{-3})
E. maidenii	1.16[a]
E. microcorys	1.3[a]
E. saligna	1.123[a]
E. tereticornis	1.19[a]
F value	**0.162**

The values observed in this study fall within the range of 1.1 – 1.5 g cm^{-3} reported as generally productive natural soils (Kolay 2000). These results are similar to those of Chanie et al. (2013) who recorded a non-significant effect of *Eucalyptus* tree plantation on soil bulk density.

3.3 Moisture content

The moisture content obtained in this study (Table 4) across *Eucalyptus* species did not show significant differences in the species' effects on soil moisture content between treatments ($p> 0.05$).

Table 4. Average moisture content observed in a study to compare the effect of four Eucalyptus species on soil properties in Ruhande Arboretum, Southern Rwanda.

Species	Moisture content (%)
E. maidenii	12.93[a]
E. microcorys	13.51[a]
E. saligna	14.19[a]
E. tereticornis	15.31[a]
F value	**0.592**

The null difference of the soil moisture under *Eucalyptus* trees was recorded which may be because the data were collected during a rainy season. This observation was in line with Chanie et al.(2013) who reported that when there is sufficient rain, *Eucalyptus* trees do not affect the soil moisture.

4 Effects of *Eucalyptus* species on soil chemical properties

Here we are presenting and discussing the results of the soil chemical analysis done by Nsabimana et al. (2008) presented in Table 5.

Table 5. Soil chemical properties in the 0-10 cm soil layer under four Eucalyptus plots in a study to compare the effect of the species on soil chemical properties in Ruhande Arboretum, Southern Rwanda (Source: Nsabimana et al. 2008).

Treatments	OC (g Kg^{-1})	Tot. N (g Kg^{-1})	C/N ratio	Avail. P (Mg kg^{-1})	pH$_{water}$	CEC (cmol Kg^{-1})	BS (%)

E. tereticornis	41.4^{ab}	3.3^{c}	12.6^{ab}	12.2^{b}	4.9^{ab}	11.9^{ab}	83.6^{a}
E. microcorys	29.8^{a}	1.9^{a}	16.3^{d}	13.2^{b}	4.5^{ab}	5.6^{a}	79.1^{a}
E. maidenii	42.3^{ab}	3.1^{bc}	13.8^{ab}	10.4^{ab}	4.2^{ab}	7.5^{ab}	59.3^{a}
E. saligna	45.2^{ab}	2.9^{ab}	15.9^{c}	14.4^{b}	4.5^{ab}	7.2^{a}	75.3^{a}
P value	0.001	0.001	0.001	0.001	0.001	0.001	0.09

SOC: Organic carbon, Tot. N: Total nitrogen, C/N: Carbon-Nitrogen ratio, Avail. P: Available phosphorus, pH: Hydrogen potential, CEC: Cation exchange capacity, BS: Base saturation

The tree species were planted on the same site with a similar land use history under the same climatic conditions. We thus base the interpretation of the results on the assumption that the current differences in soil chemical characteristics reflect the influence of the planted trees. In addition, the plots under study were planted at different times thus the ameliorative effect of the trees became more distinct with the increasing age of the plantation and the studied parameters were likely to be influenced by the species-specific litter chemical quality.

4.1 Soil pH

The topsoil of the study area was rated as strongly acidic ranging between 4.2 and 4.9 (Landon 1991). The acidity may be attributed to (1) Input of organic acids from litter decomposition and root exudates, (2) Increased proton release in the soil to compensate for the high plant uptake and storage of base cations (Jobbágy and Jackson 2003) as stated by (Rwibasira et al. 2021) and (3) Abundant rainfall which causes the leaching of calcium and magnesium ions and lowers soil pH (Zhao et al. 2018).

Soil acidification under *Eucalyptus* species was reported in previous studies conducted at this site (Nsabimana et al. 2008), in forest plantations near this site (Mugunga et al. 2015), and in other tropical (Laclau et al. 2010) and non-tropical regions (Rhoades and Binkley 1996). The relatively high soil pH under the *E. tereticornis* (compared to the other three species) plot may be due to its canopy cover, which may lead to increasing volumes of leaf litter (Liang et al. 2016). Similarly, Mensah (2016) found reduced soil pH and strongly acidic values ranging from 3.5 to 4.0 under *Eucalyptus* species plantations in the Koga watershed in Ethiopia. The results were in line with Sarker et al. (2022) who reported a lower pH in the plots planted with *Eucalyptus*.

4.2 Soil organic carbon and carbon-nitrogen (C/N) ratio

Soil organic carbon (SOC) varied from 2.98 to 4.52 % and ranged under high levels according to (Landon 1991). The result was in line with Leite et al. (2010) who found in Brazil that contents of soil organic matter (SOM) were considerably higher in *Eucalyptus* species soils than in pasture areas. They attributed this to the greater amount of residues produced by the *Eucalyptus* species plantation (leaves, branches, bark, and especially roots) that remained in the soil. Mengistu et al. (2020) observed the highest percentage of OC and OM in the soil under *Eucalyptus* plantations than in cropland and therefore grouped under high concentration levels. The result was supported by the findings by Alemayhu and Yakob (2020) who reported high SOC under *Eucalyptus grandis* and *Eucalyptus saligna* and Lemma et al. (2006), who showed that *E. grandis* plantation, after 20 years of cultivation and 35 years of pasture, increased the total soil organic carbon to nearly pre-deforestation levels. The relatively high SOC in *E. saligna, E. maidenii,* and *E. tereticornis* may be attributed to (1) high amounts and quality of plant residues and the recycling of nutrients through the decomposition of different tree parts, (2) the potential of building large amounts of biomass than any other tree species (Rwibasira et al. 2021).

The values of C/N ratio ranged from 12.55 to 15.68 in the topsoil. According to Landon (1991), the quality of SOM in topsoil studied was good, with values, indicating good quality SOM. The value <25 means that decomposition may proceed at the maximum rate possible under environmental conditions while organic matter with a high C/N ratio (>20) also locks up nitrogen as it decomposes, decreasing the availability of nitrogen to the plants.

4.3 Total nitrogen (TN) and available phosphorus (P)

Nitrogen varied from 0.19 – 0.33%, rated as high as stated by (Hazelton and Murphy 2007). The results were in line with the findings by Alemayhu and Yakob (2020) who found higher levels of nitrogen under *Eucalyptus* than on agricultural land and Yitaferu et al. (2013) who found greater total nitrogen concentration in *Eucalyptus* land use than others. However, some researchers reported contradictory findings. Mensah (2016) and (Sarker et al., 2022) reported low total available N under *Eucalyptus* spp. Plantations, which they attributed to high nutrient demand by *Eucalyptus* spp. (Laclau et al. 2010). The significant differences and high levels of TN in the study could be explained by: (1) the significantly different quantities of organic matter, due to the obvious difference in leaf litter (Liang et al. 2016), (2) higher litter production and its relative faster rate of decomposition and microorganisms break down, which increased organic matter input in the soil generating more nutrients, including nitrogen.

The available P varied from 10.4-14.4 mg kg^{-1}. This is classified as below the medium sufficiency range (Carrow et al. 2004). The relatively lower available P in the study area may be due to the low pH value which might have resulted in a higher amount of soil available P accumulated on the soil surface by adsorption (Mensah, 2016). In addition, the *Eucalyptus* species have a higher capacity of immobilizing phosphorus thus making it inaccessible for plant use (Aweto and Moleele 2005). When soil pH is below 5.5, soil trace nutrients like Aluminium (Al) availability increases to levels that are unsuitable for most plant growth and soil soluble P tends to form insoluble compounds with Al and Iron (Fe) in acidic soils (Berendse 1998).

4.4 Carbon exchange capacity (CEC) and base saturation (BS)

The CEC varied from 7.2-11.0 Cmol Kg^{-1}, arrange rated as low (Table 5) according to (Metson 1961) as stated in the soil test results manual by Hazelton and Murphy (2007). Mensah (2016) also reported low CEC under *Eucalyptus* plantations in Kenya. The low values are contributed to by the kaolinite and sesquioxide or oxidic clays, which are dominant clay minerals in highly weathered soils, lacking negative charges. Consequently, they do not retain adsorbed cation and end up with low CEC due to the low nutrient retention capacity (Landon 1991). In addition, the higher CEC value under *E. tereticornis* can be attributed to higher soil organic matter content (Tomašić et al. 2013).

Base saturation (BS) is rated as moderate under *E. maidenii*, high under *E. saligna* and *E. microcorys,* and very high under *E. tereticornis* (Table 5) according to Metson (1961). Aweto and Moleele (2005) indicated that low soil pH leads to low soil BS. However, the results of the study showed that BS was high regardless of the low pH observed. This may be attributed to the production and the release of organic acids by plants and microorganisms into the soil solution as a "nutrient acquisition strategy", which may lead to an exchange acidity dominated by protons, allowing for high BS (Fujii, 2014). The results were in line with the findings by Lemma et al. (2006) who noticed high BS under *E. grandis.*

5 Conclusions

Different *Eucalyptus* species did not affect soil physical properties differently. Significant differences were recorded between *E. tereticornis* and *E. maidenii* tree species in sand percentage only. The higher percentages of sand indicate that the soil was sandy. Soil organic carbon and total nitrogen were high in the soil under all tested *Eucalyptus* species, which is unusual because of their high demand for nutrients. Several studies have reported a decreased level of nutrients in the soil under *Eucalyptus* plantations, which was contradicted by the present study. This shows that *Eucalyptus* spp. not only deplete nutrients in the soil under which they are planted but also can contribute to its nutrient increase. Therefore, the effects of *Eucalyptus* species on soil properties remain unclear. It is important to make observations where the benchmark state of the study site is recorded to enable differences in the species effects on the site if any. Further, well-designed studies need to be made to test if the species similarly affect soils or not and confirm if the species increase soil nutrients.

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