

Effects of Tree Forest Plantations on Soil Physicochemical Properties in the Arboretum of Ruhande, Southern Province of Rwanda

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Abstract

Different tree species are blamed to have negative effects on soil ecosystems by changing soil physicochemical properties, and hence soil quality. However, few researches to verify this statement were done in Rwanda. This study provides prior information on the effects of planted forest tree species on soil physicochemical properties. It was conducted in the Arboretum of Ruhande, in southern Rwanda. Soil cores were collected in plots of exotic, native and agroforestry tree species. Collected soils were analysed for soil pH, total nitrogen, organic carbon, available phosphorus, aggregate stability, bulk density, soil humidity, cation exchange capacity, and soil texture. Soils sampled under exotic tree species were acidic, rich in soil organic carbon, and in soil available phosphorus. Native and agroforestry tree species offer better conditions in soil pH, soil water content, cation exchange capacity, clay and silt. Less variations in soil total nitrogen and soil bulk density were found in soils sampled under all studied forest types. Research concluded that studied tree species have different effects on soil physicochemical parameters. It recommended further studies to generalize these findings.

Key words: soil, exotic, native, agroforestry, soil properties

1. Introduction

Soil is the dominant ecosystem that serves as the storage of transformed organic substances mainly the recycled soil organic carbon (Vignozzi et al. 2019). Soil contributes to the control of water fluxes, and it is the suitable habitat for different terrestrial animal species (Rietz and Van der Putten 2012). Agriculture cannot take place, and different plant communities cannot exist without soil. Around 7% of the total global soil ecosystem is used for forest plantations (Wood 2018; Jürgensen et al. 2014). Different tree species were mainly planted to provide timber, food for humans and animals, fire wood, medicines, opportunities for recreation and

tourism (Campos et al. 2005). They were also planted for climate and erosion control, carbon sequestration, and for biodiversity conservation (Dyck 2003; Mishra et al. 2003).

Despite the increase in global area used for forest plantations and their importance to human well being, the implications of forest plantations on soil physicochemical properties remain an interesting topic in environmental studies. The difference between exotic, native and agroforestry tree species was mainly explained by the impacts that each tree species may have on soil quality and soil biodiversity (Sjoerd et al. 2018). Some exotic tree species are criticised to increase soil acidification, and consume high water quantity and soil nutrients, particularly in monodominant stands (Henok et al. 2017; Tesfaye et al. 2016; Jagger and Pender 2003). Agroforestry tree species are appreciated to improve soil fertility and hence the agricultural productivity (Ospina 2017). Native tree species are recognized to enhance biodiversity conservation of wild species and to maintain soil quality (FAO 2014).

Planting tree species such as *Ficus* (*Ficus thonningii*), *Erythrina* (*Erythrina abyssinica*), *Euphorbia* (*Euphorbia tirucalli*), and *Vernonia* (*Vernonia amygdalena*) was a tradition of Rwandese. These species were mainly used to make compounds around houses (AFF 2011). Reinforcement for planting woody and perennial trees out of household started around 1920 (AFF 2011). Planted tree species include *Eucalyptus*, *Pinus*, *Acacia*, *Entandrophragma*, *Podocarpus*, and *Polyscias* (GoR 2007). The total forest cover of Rwanda's forest plantations is now 428 569 (13%) hectares (GoR 2014), with the target to attain 30% by 2020. Planted forests were introduced to replace natural forests, to protect soil against erosion, and to create buffer zones around natural and protected areas. They were also planted for the production of firewood, fruit and timber, and for increasing the construction materials (AFF 2011).

Effects of planted tree species on soil physicochemical properties are less studied in Rwanda. Some studies focused on carbon stock and fluxes in natural and forest plantations (Nsabimana 2009). Few studies explored the relationships between planted tree species and soil physicochemical parameters indicating the conditions of soil quality. This research provides prior and updated information in relation to the effects of some forest tree species on soil pH, nitrogen, phosphorus, soil organic carbon, aggregate stability, cation exchange capacity, soil water content, soil texture and soil bulk density. Research tested the hypothesis that (1) soil properties differ significantly between studied tree species, and (2) introduced tree species have more negative effects on soil properties than indigenous tree species.

2. Materials and methods

2.1. The area of study

Samples were collected in the Arboretum of Ruhunde (2°36'S and 29°44'E, Altitude: 1737m) located in southern Province of Rwanda. The Arboretum is dominated by tropical humid climate. The average annual temperature is around 20°C, and the average annual precipitation is estimated at 1232mm (GoR 2018). The soil of the area is a Ferralsol formed from schists

and granites mixed with mica schist and quartzite (Nsabimana 2008; Verdoodt and Van Ranst 2003). The top soil pH was between 3.9 and 5.4 (Nsabimana et al. 2009). The Arboretum of Ruhande was inhabited by human population and used as a crop land to 1933 (Nsabimana et al. 2009). Its current size is around 200ha, comprising 504 plots, each having the size of 50x50m. Plots are numbered and each of them has an historical database of plant growth measurement and plant management (Nsabimana 2008). Each plot is used for forest plantations dominated by different introduced and indigenous tree species.

Table 1: Treatments, pseudo-replicates plot numbers, stand age and geographic locations of sampled tree plot species in the Arboretum of Ruhande, southern Rwanda.

Tree species	Category	Plot number	Stand age (years)	Latitude	Longitude	Altitude
<i>Calliandraca lothrysus</i>	Agroforestry	265	34	26° 7' 5.16" N	29° 45' 13.212" E	1710
		267	34	26° 7' 7.68" N	29° 45' 10.836" E	1709
		273	34	26° 6' 54.72" N	29° 45' 18.144" E	1705
<i>Cedrelasserata</i>	Agroforestry	56	36	26° 9' 45.36" N	29° 44' 49.488" E	1729
		111	74	26° 8' 29.76" N	29° 45' 18.288" E	1731
		36	82	26° 7' 26.76" N	29° 45' 36.684" E	1709
<i>Senaspectabilis</i>	Agroforestry	100	78	26° 8' 27.24" N	29° 45' 20.664" E	1712
		258	69	26° 9' 15.12" N	29° 45' 25.308" E	1709
		264	69	26° 9' 4.32" N	29° 45' 29.844" E	1710
<i>Eucalyptus grandis</i>	Exotic	181	-	26° 10' 22.08" N	29° 44' 50.208" E	1711
		218	68	26° 10' 21.72" N	29° 44' 51.972" E	1711
		220	68	26° 6' 48.96" N	29° 45' 37.944" E	1698
<i>Eucalyptus maideni</i>	Exotic	1	85	26° 9' 13.32" N	29° 44' 48.336" E	1734
		179	73	26° 6' 51.48" N	29° 45' 36.036" E	1702
		377	70	26° 5' 45.6" N	29° 45' 20.628" E	1679
<i>Grevillea robusta</i>	Exotic	104	78	26° 9' 51.48" N	29° 44' 58.164" E	1710
		150	35	26° 9' 56.88" N	29° 45' 12.996" E	1727
		322	39	26° 8' 23.64" N	29° 45' 30.096" E	1707
<i>Entandrophragm aexcelsum</i>	Native	44	70	26° 9' 7.92" N	29° 45' 08.172" E	1734
		54	67	26° 8' 13.92" N	29° 45' 25.848" E	1719
		78	67	26° 7' 57.36" N	29° 45' 34.092" E	1708
<i>Podocarpusfalcat us</i>	Native	156	72	26° 10' 9.48" N	29° 44' 56.868" E	1708
		196	-	26° 9' 39.24" N	29° 45' 03.348" E	1710
		226	67	26° 8' 25.44" N	29° 45' 38.124" E	1697
<i>Polisciasfulva</i>	Native	240	69	26° 9' 46.44" N	29° 45' 09.036" E	1713
		262	69	26° 9' 6.12" N	29° 45' 28.728" E	1711
		268	69	26° 8' 52.8" N	29° 45' 33.912" E	1700

2.2.Data collection

During this study, soil cores were collected in different tree species. Specifically, they were collected in indigenous (native) tree species comprising *Polysciasfulva*, *Podocarpusfalcatus*, and *Entandrophragmaexcelsum*. Samples were also collected in introduced (exotic) tree species composed of *Eucalyptus grandis*, *Eucalyptus maideni*, and *Grevillea robusta*. Further, samples were collected in agroforestry tree species, namely *Calliandracaalothrysus*, *Cedrellaserrata*, and *Senaspectabilis*. In each type of forest tree species, three pseudo-replicates were selected. In each pseudo-replicate, data were collected in nine sampling points, each having the size of one-meter square, and in 0-10 cm soil layer depth. The plot number of each pseudo-replicate, age, geographic location and altitude are given in Table 1.

Reference to the research conducted by Nsabimana et al. (2008), a distance of 10m from the edge of the sampling plot was left outside of the area of study to reduce edge effects. Further, to minimize the autocorrelation, a distance of 16m was maintained between two sampling locations, based on the methodology used by Clark et al. (1996). Samples from the same replicate were bulked together to make one representative sample (Sayad et al. 2012). Samples used for the analysis of soil bulk density were collected following the core sampling method developed by Abu-Hamdeh and Al-Jalil(1999). Finally, each sample was taken to the laboratory of soil analysis and separately analysed for soil properties.

2.3.Laboratory and statistical data analysis

Each soil sample was dried and sieved before starting laboratory analysis. After, the suspension made of soil and water was obtained by mixing water with soil at 1:1.5 ratio (Tellen and Yerima, 2018). Then the pH water (pH_w) levels were calculated by using a calibrated pH-meter (Watson and Brown 1998) for each sample. Due to the existence of different types of soil nutrients, the total nitrogen and available phosphorus that are essential for plants were taken into consideration. These nutrients together with the soil organic carbon, cation exchange capacity, bulk density, aggregate stability, water content and texture were calculated following their specific measurement techniques (Nsengimana et al. 2018).

Means within three pseudo-replicates for each treatment of studied tree species were analysed. Effects of tree species were analysed by the non-metric multidimensional scaling (NMDS) following the index of similarity developed by Bray-Curtis (Ashford et al. 2013). Further, the Bray-Curtis dissimilarity analysis was carried out to determine which parameter contributes most to the similarity (Clarke 1993). The ANOVA based on the tests developed by Kruskal-Wallis for equal medians helped to assess differences in soil physicochemical characteristics between plots of introduced, agroforestry and indigenous tree species. Linear correlation coefficients developed by Pearson were used to determine correlations in soil physicochemical parameters, and significant differences were tested at 5% probability level. The PAST software 3.09 was preferred to run these statistical analysis (Hammer et al. 2001).

3. Results

The mean-age of studied tree species varied from agroforestry (56.6 ± 21.4), introduced (64.5 ± 17.9) to indigenous (69.7 ± 1.7) tree species. Variations in soil physicochemical parameters were not related to the age of studied tree species, and the non-metric multidimensional scaling tests indicated less impacts of studied tree species on soil properties (ANOSIM = 0.3, $P > 0.5$). However, significant differences ($P < 0.05$) were found in studied soil physicochemical parameters. This was supported by the analysis of the overall similarity index (OSI = 7.88; $P < 0.05$). The Bray-Curtis similarity index (SI) indicated high similarities between blocs of agroforestry and indigenous tree species (SI = 0.97, $P > 0.05$), and between blocs of agroforestry and introduced tree species (SI = 0.85, $P > 0.05$). Less similarities were found between blocs of introduced and indigenous (SI = 0.63, $P < 0.05$) tree species.

Higher levels in soil pH were found in plots of indigenous and agroforestry tree species compared to the plots of introduced tree species (Table 2). Despite low levels in soil pH, plots of introduced tree species have higher levels in soil organic carbon, while plots of agroforestry and indigenous tree species have almost the same levels in soil organic carbon (Table 2). There are slightly significant differences ($P < 0.05$) in soil total nitrogen between plots of indigenous, agroforestry, and introduced tree species (Table 2). Further, plots of introduced tree species are suitable for soil phosphorus compared to the plots of indigenous and agroforestry tree species. However, these differences were not significant ($P > 0.05$).

Table 2: Variations in soil physicochemical parameters (Mean \pm SD) under agroforestry, exotic and native tree species in the Arboretum of Ruhande in southern Rwanda

Tree species		pH	SOC (%)	Tot. N (%)	Av. P (mg/kg)	CEC (Meq)	AS (%)	W. cont. (%)	Clay (%)	Silt (%)	Sand (%)	BD (g/cm ³)
Agroforestry	Mean	5.4	6.5	0.6	3.4	7.4	0.5	24.4	14.8	18.0	67.2	0.9
	SD	0.3	0.7	0.3	1.6	0.3	0.1	1.8	6.6	4.3	10.9	0.2
Exotic	Mean	5.0	9.5	0.6	4.4	7.0	0.6	19.9	14.4	16.3	69.9	0.9
	SD	0.2	3.2	0.3	1.0	0.3	0.1	5.2	2.3	0.3	1.9	0.0
Native	Mean	5.9	6.4	0.5	3.3	7.8	0.6	25.2	13.4	16.9	68.8	0.7
	SD	0.4	0.4	0.1	0.6	0.5	0.2	4.7	1.9	2.1	3.93	0.2

SD: Standard Deviation, Tot N: Total Nitrogen, SOC: Soil Organic Carbon, Av. P: Available Phosphorus, Ag. Stab: Aggregate stability, BD: bulk density, W. cont.: Water Content, CEC: Cation Exchange Capacity.

Soil under plots of indigenous and agroforestry tree species indicated better conditions in cation exchange capacity than the plots of introduced tree species (Table 2). Small significant differences ($P < 0.05$) in soil aggregate stability were found under plots of agroforestry tree species, while plots of introduced and indigenous tree species have the same proportions in aggregate stability (Table 2). Other significant statistical differences were found in soil

texture ($P < 0.05$). Furthermore, soils sampled under plots of indigenous and agroforestry tree species were rich in soil water content. This was found to be 25.2 ± 4.7 under plots of indigenous tree species and 24.4 ± 1.8 under plots of agroforestry tree species. Lower levels in water content were found in plots of introduced tree species (19.9 ± 5.2).

The ANOVA test between introduced, indigenous and agroforestry tree species indicated significant difference between sample medians ($\chi^2 = 31.5$; $DF = 8$; $P < 0.05$). Even though there is no significant statistical differences between agroforestry and indigenous tree species ($\chi^2 = 11.7$; $DF = 5$; $P > 0.05$); significant differences were found between agroforestry and introduced tree species ($\chi^2 = 20.69$; $DF = 5$; $P < 0.05$), and between introduced and indigenous tree species ($\chi^2 = 18.7$; $DF = 5$; $P < 0.05$). The Pearson linear correlation analysis indicated a positive correlation between all studied soil physicochemical parameters, while few of them showed significant ($P < 0.05$) statistical differences (Table 3).

Table 3: Pearson correlation coefficients between soil physicochemical properties under plots of agroforestry, native and exotic tree species

	SOC	Tot N	Av. P	CEC	Ag. Stab	Hum	Clay	Silt	Sand	BD
pH	0.31	0.56	0.49	0.02*	0.65	0.23	0.58	0.59	0.72	0.32
SOC		0.87	0.18	0.29	0.35	0.07	0.89	0.28	0.41	0.01*
Tot N			0.95	0.58	0.79	0.79	0.02*	0.85	0.72	0.88
Av. P				0.47	0.16	0.26	0.93	0.1	0.23	0.17
CEC					0.64	0.22	0.6	0.57	0.7	0.3
Ag. Stab						0.42	0.77	0.06	0.06	0.33
Hum							0.81	0.36	0.48	0.09
Clay								0.83	0.7	0.9
Silt									0.13	0.27
Sand										0.4

*Tot N: total nitrogen, SOC: soil organic carbon, Av. P: available phosphorus, Ag. Stab: aggregate stability, BD: bulk density, Hum: humidity, CEC: cation exchange capacity, *Significant differences at the 5% probability level*

4. Discussion

Actually, soil pH is used to measure the soil acidity and soil alkalinity. In this regard, the main purpose is to determine the conditions for plant growth, variations in soil nutrients and the levels in soil microbial activities (Wodaja and Alemayehu 2014). In Rwanda, a previous study indicated that soil with pH less than 7.3 is generally acidic (Nabahungu 2013). This study classified soil acidity into different subgroups. The first one contains moderately acidic soils, having the pH ranging from 5.6 to 6.0. The second one concerns strongly acidic soils having the pH ranging from 5.1 to 5.5. The last subgroup is that of very strongly acidic soils with the pH ranging from 4.5 to 5.0. Relating this classification with the findings of this study,

soils under introduced tree species were very strongly acidic. Those under agroforestry were strongly acidic, while those under indigenous tree species were moderately acidic.

Acidic soils under plots of exotic tree species found in this study were also found in another study done in southern Rwanda (Nsabimana et al. 2009). Different studies in relation with this one showed that high levels in soil pH under exotic tree species might be related to the availability of exchangeable base cations (Sharma 2011), and to the decrease in base forming cations along the ongoing uptake of nutrients by tree species (Abegaz and Adugna 2015).

Even though soil under exotic tree species have high acidity, they offer better conditions in soil organic carbon. Other studies indicated that variations in soil organic carbon are influenced by the litter fall added to the soil from trees and shrubs (Worku et al. 2014), dead roots, and biochemical activities of mycorrhizal fungi as well (Lemma et al. 2006). Actually, the richness in soil organic carbon is very important for soil ecosystems. Soil organic carbon was also appreciated to supply nutrients in soil, facilitate soil exchange of cations, soil aggregation, and increase the capacity of soil to hold water. In addition, different activities of soil biodiversity are controlled by soil organic carbon (Dudal and Deckers 1993).

Results of this study indicated slight differences in soil total nitrogen across all studied plots, while high levels of available phosphorus were found in plots of introduced tree species. These organic matters supply water and nutrients in soil, and provide suitable physical conditions to plant diversity. Concentration of nitrogen were found to be influenced by fine roots of tree species, and hence doesn't vary significantly, exception for nitrogen fixing trees (Shin et al. 2018). However, this is not the case for available phosphorus which is mainly influenced by soil pH (Mugoboka 2008). This is in relation with this study, where soils under introduced tree species were acidic and have high levels in phosphorus.

Plots of agroforestry and indigenous tree species offer better conditions in soil cation exchange capacity. This soil parameter is used for measuring the levels of cations used to supply soil nutrients, the capacity of soils for retaining water, and to measure the levels of cations that are readily to be exchanged for the neutralization of negative charges (Wodaja and Alemayehu 2014). Variations in cation exchange capacity is controlled by leaching of exchangeable ions coming from top soils (Nsabimana et al. 2008). In forest plantations, these exchangeable ions are probably increased by high levels of litter fall from tree species, shrubs and herbs (Kassa et al. 2017). They might be also related to the activities and symbiosis of mycorrhizal fungi that reinforce the decomposition rate (Sharma 2011; Howard et al. 1999).

Indigenous tree species were also found to offer better conditions in bulk density and in levels of soil water content. Soil water content was found to be mainly related to less human activities, and high availability of soil organic matters that offer better soil aggregation (Bini et al. 2013). Other studies concluded that soil bulk density is a key factor controlling soil-water holding capacity. The lower is the aggregate stability, the more soil holds water, and more soils contain high water quantity (Cardoso et al. 2013; Tejada et al. 2006). For this

study, there is no much variations in aggregate stability. We conclude that soil water holding capacity might be influenced by other factors different from the aggregate stability.

Differences in soil texture were found across studied plots. Soil texture is mainly used for estimating soil water availability depending on the land use and land management (Beutler et al. 2002). In soil studies, soil texture is an indicator of water retention and water transport. It is used for evaluating the levels of soil erosion, and for estimating the variability in soil structures (Doran and Parkin 1994). Small differences in soil texture found in this study were related to the structure of Arboretum tree forest plantations, dominated by shrubs, and to the well-developed canopy. This is supported by the findings of another study, where clay and silt soil fractions may be influenced by the canopy of plant diversity, and the protection of root system from leaching and erosion by surface litter coming from trees (Yeshaneh 2015).

5. Conclusion

The present study showed that studied tree species affect differently soil physicochemical parameters despite the age. It was found that soils under plots of introduced tree species were acidic, compared to those under indigenous and agroforestry tree species. Introduced tree species offer better conditions in available phosphorus, soil organic carbon, and sand soil, while plots of agroforestry tree species offer better conditions in silt and clay. Indigenous tree species offered better conditions in soil bulk density, water holding capacity, pH, and cation exchange capacity. This research revealed that indigenous tree species offer better soil conditions, while agroforestry can serve as alternative. It recommended further studies to assess effects of tree forest plantations in other regions of Rwanda to validate these findings.

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