



Sustainable Agroforestry for Soil Chemical Properties Improvement and Nutrients Availability in Agriculture Landscape around Cyamudongo Isolated Forest, Rwanda

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ABSTRACT

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The protected areas of Rwanda are facing various challenges resulting from the anthropogenic activities of the surrounding communities, especially in the adjacent area to Cyamudongo isolated rain forest, which results in soil degradation. Therefore, this study aims to broaden current knowledge on the impact of sustainable Agroforestry (AF) on soil-selected chemical and physical properties. To understand this, the permanent sample plots (PSPs) were established mainly in the designed four transects of four km long originating on the boundary of the Cyamudongo isolated rain forest following the slope gradient ranging from 1286 to 2015 m asl. A total number of 73 PSPs were established in the Cyamudongo study area. The Arc Map GIS 10.4 was used to design and map the sampling areas while GPS was used for localization of plots centers. Statistical significance was analyzed through R-software. The recorded soil pH means value across in Cyamudongo study area is 4.2, which is strongly acidic. The tests revealed that the soil pH, C, N, C: N ratio, OM, NH₄⁺, NO₃⁻+NO₂⁻, PO₄³⁻, and CEC were significantly different in various soil depths. The pH, N, C: N ratio, CEC, NH₄⁺, PO₄³⁻, and Al₃⁺ showed a significant difference across land uses whereas the C and NO₃⁻+NO₂⁻ did not show any statistical difference. All tested chemical elements showed a statistical difference as far as altitude ranges are concerned. The only NH₄⁺, PO₄³⁻, and CEC showed significant differences with time whereas all other remaining chemical elements did not show any statistical significance. The soil pH was very strongly correlated with CEC, Mg, and Ca in cropland (CL) whereas it was strongly correlated in both AF and natural forest (NF) except for Mg, which was moderately correlated in AF. Furthermore, its correlation with K was strong in CL, and moderate in AF while it was weak in NF. Finally, the pH correlation with Na was weak in both AF and CL whereas it was negligible in NF.

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Introduction

Background

In Rwanda, Agroforestry (AF) was seen as a net positive that could generate a flow of concrete benefits for smallholder farmers and make a significant contribution both to rural development and environmental protection and enhancement (Stainback et al., 2012). The adoption of AF and trees outside forest techniques will be enhanced to contribute to overall forest resources and agriculture productivity. AF is the most wide-reaching restoration opportunity in Rwanda. The agriculture sector holds a key role in sustaining efforts to improve agricultural

productivity and addresses the challenge of soil degradation through the promotion of AF practices and forest management. The countries with a high population density especially Rwanda, experience the problems associated with the management of soil including poor soil productivity and the increase of erosion if no action is taken (König, 1994). Furthermore, Olson and Berry, (2003) pointed out that land degradation has long been recognized as a major problem in Rwanda, especially impacting the Southwest of the country, but important everywhere.

The broader agriculture community and policymakers must pay increased attention to AF as a viable strategy to restore and sustain soil health (Dollinger and Jose, 2018). According to König, (1994), erosion control by the use of biological measures such as multi-purpose hedges, and transformation of traditional land-use systems into appropriate AF systems is better than mechanical erosion control such as erosion control ditches.

AF For Soil Properties Improvement and Nutrients Availability

Changes in land use can significantly affect soil properties (Haghighi et al., 2010). The soil exchangeable bases in AF systems are higher than in natural forests (NF) due to the adoption of adequate soil conservation measures and scheduled fertilizer application, which contribute to the increase in the available macro and micronutrient status throughout the soil profile (Majumdar et al., 2016). The term soil fertility has been used by Lundgren and Nair, (1985) to refer to “the capacity of soil to support the growth of plants, on a sustained basis, under given conditions of climate and other relevant properties of the land”. The well-managed AF system helps to address soil-related issues such as soil degradation and fertility depletion (Lundgren and Nair, 1985). The proper selection of tree species in the AF system that can fix the atmospheric N may help the soil to receive a considerable amount of N and other essential nutrients needed by associated crops (Lundgren and Nair, 1985). Both N-fixing and non-N-fixing trees are an AF that is general practice in tropical Africa. The AF practice positively affects soil health through nutrient recycling through the system (Jose, 2009). The AF tree species have been shown to significantly affect the soil properties and nutrients (pH, OC, NH_4 , P, Na, K, Ca, and Mg) with different magnitudes according to species. It is recommended that tree planting or Farmer Managed Natural Regeneration (FMNR) in AF parklands is guided not only by the common objectives of improving soil fertility and producing food and fodder, but also consider the selection of the appropriate tree species (Diallo et al., 2019). The AF trees provide the soil organic matter (OM) that is the energy source of soil organisms and influences both soil biodiversity and associated soil biological functions. As a result, SOC is one of the important indicators used in assessing soil health (Dollinger and Jose, 2018). AF is a practice that offers great promise to improve soil and soil health for current and future generations. The broader agriculture community and policymakers must pay increased attention to AF as a viable strategy to restore and sustain soil health (Dollinger and Jose, 2018).

This study assessed the impacts of sustainable AF land use on the selected soil chemical properties through time, in different ranges of soil depths (0-20, 20-40, and 40-60 cm) and altitudes (>1200 m asl and <2100 m asl). It evaluated the change of selected soil chemicals properties (pH, C, N, C: N ratio, OM, NH_4^+ , $\text{NO}_3^- + \text{NO}_2^-$, PO_4^{3-} , and CEC) of ongoing land-use of sustainable AF in the study area of Cyamudongo Project intervention. The study alternatively hypothesized that There is a significant difference of selected soil chemical properties in different soil depths, land uses, altitude ranges, and throughout the time in the study area.

Materials and Methods

Description of the Study Area

Rusizi District is located in the South-West of Rwanda and is one of seven districts of the Western Province. The area of the Rusizi district is 959 km². In its south, it is bordered by two countries including the Democratic Republic of Congo (DRC) and the Republic of Burundi whereas, in its north, it is bordered by Nyamasheke and Nyamagabe districts. Furthermore, in its East, it borders with Nyamagabe and Nyaruguru districts. The estimated population density is 420 inhabitants km⁻². Three sectors of Rusizi District including Gitambi, Nkungu, and Nyakabuye of Rusizi District located in the community around Cyamudongo isolated forest were selected because they were the main intervention area of the Cyamudongo Project. Cyamudongo fragmented rain forest (02°33.12'S 28°59.49'E) is a small dense forest patch (300 Ha) around 8 km away from Nyungwe National Park (NNP) in its South and western parts (Figure 1).

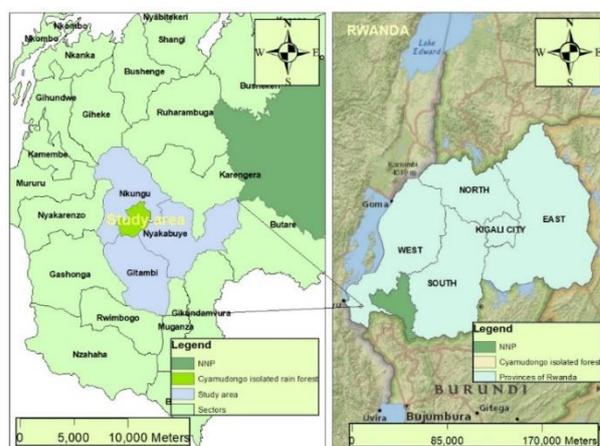


Figure 1. Location of Cyamudongo study area

Sampling design

In this study, four transects were designed by the use of ArcMap software 10.4 in the way that each transect has 4 km originating from Cyamudongo fragmented rain forest boundary towards Bugarama downhill via the high mountains of Nyakabuye and Gitambi sectors of Rusizi district. Its orientation towards Bugarama downhill was made to integrate all possible variations across the field since the field is characterized by the big mountains with steeper slopes with altitude ranging between 2015 at the top and 1282 m asl at their bottoms (Figure 2). The initial point of the transect was randomly selected. The four km transect corresponds to the width of the buffer established by the Cyamudongo Project. The distance of 600 m was kept between two consecutive transects. Systematically, the distance from one plot to the next within the transect was respected corresponding to 250 meters that were consistently measured to represent the variability of the field across the study area. The plots fallen in AF land use were counted while those fallen in forest land use were removed from the scope of our study. A total of 61 plots were established with a 17.84 m radius equivalent to approximately 1000 m² to take soil samples. The sampling design for soil sample collection inside Cyamudongo fragmented rain forest was established along transects by

counting 250 m from the boundary of the forest. The starting point of transects of both inside and outside Cyamudongo fragmented rain forest was the same (Figure 2). The distance between and within transects was respected. The sampling plots were established on 3 transects constituting the undisturbed forest by human activity. Therefore, 12 plots for soil sampling were established along 3 transects. The ArcMap software 10.4 was used to establish transects, GPS to take geographic coordinates of plots every 250 meters along the transect, and Hipchain to measure ground distance.

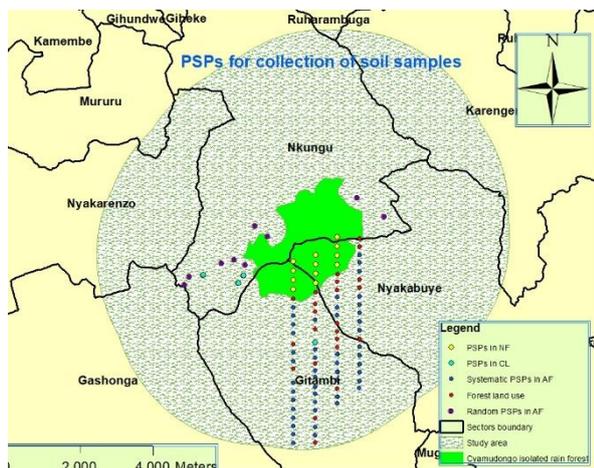


Figure 2. Soil sampling design both in and outside Cyamudongo fragmented rain forest

Collection of Soil Samples

Through the use of the soil Auger 305.05, I was able to gather the samples of soil in various sampling depths (0-20 cm, 20-40, and 40-60 cm) to test the chemical variables of the soil. For each plot, three samples were systematically taken for each depth to make a composite sample. The soil samples were put in open paper bags in the room for about three weeks to allow them naturally to be dried. Later the soil was put in plastic and paper bags, sealed, labeled, and transported to the laboratory of the University of Koblenz-Landau for analysis. A total number of 475 soil samples were collected at different times of data collection with respect to sampling various depths both in the forest and outside the forest.

Description of Laboratory Work

The Soil Organic Carbon (SOC) was tested following Walkley and Black, (1934) and was converted into the Soil Organic Matter (SOM) by the use of a default factor of 1.724 that was multiplied by the % of SOC. Total N was tested following Bremner & Mulvaney, (1982).

The C: N ratio was calculated from the following equations:

$$[C: N = (\text{Soil organic C} : \text{Total N})] \quad (1)$$

Soil pH was measured potentiometrically in CaCl_2 at a ratio of 1:7.5 Soil: CaCl_2 following the procedure of (Okalebo et al., 2002). Available phosphorus was extracted from the soil using Bray No 1 solution as an extractant. Furthermore, extractable nitrate was determined by the colorimetric method. Soil samples were extracted with potassium sulfate after which salicylic acid and sodium

hydroxide were added and then analyzed by the molybdenum blue method. The exchangeable bases were analyzed following Chapman, (1965). The CEC was determined using a similar procedure as for exchangeable bases.

Statistical Analysis

The software package used to analyze the data was R software. A *Kruskal Wallis test* (the non-parametric equivalent of an ANOVA) was used to compare soil nutrients in different soil depths. As the automatic contrast procedure which exists for ANOVA is not developed for *Kruskal Wallis tests*, a pairwise difference between soil depths using a separate *Mann Whitney Wilcoxon test* was used at the $P < 0.05$ level. *Spearman correlation test* was used to detect the relationship between selected soil variables. The soil depths, land use, altitude ranges, and time were considered as independent variables and various variables of soil as dependent factors.

Results and Discussions

The average means of pH, C, N, C: N ratio, OM, $\text{NO}_3^- + \text{NO}_2^-$, NH_4^+ , PO_4^{3-} , CEC, and Al^{3+} in different soil depths, land uses, and altitudes ranges were obtained from the analysis. The averaged pH values are 4.51, 4.41, and 4.34 in 0-20 cm, 20-40 cm, and 40-60 cm respectively and the averaged pH value in all soil depths is 4.42. For all plots in the study area, a pH decreased downward with soil depths where the subsurface soils are more likely to be acidic than in topsoil. There was a significant difference in pH value among soil layers ($p\text{-value} = 0.022$). The obtained pH values were strongly acidic according to Horneck, et al., (2011). This is in complete agreement with Adhikari et al., (2014) who reported more pH averaged values on surface layers that decreased with the increase of soil depths. This result also fits well with Reeves & Liebig, (2016) who reported a pH that varied significantly with soil depths. The tests highlighted the difference in pH values for various land uses. The soil pH mean values in AF, CL, and NF were 4.47, 4.10, and 4.15 respectively. This concurs well with Endalew, (2016) who found that the land-use type affects significantly the pH level and the lowest pH values were observed in CL and NF. He further confirmed that the low pH level in CL might be due to the poor management of the soil such as the gathering of crop residues and application of acidic fertilizers among others. This result shares a number of similarities with Tkassahun et al., (2009) who indicated a significant statistical difference among various land uses with strong acidic pH for CL and browsing areas. On the other hand, Tkassahun et al., (2009) found that the NF contains more pH values. The soil pH values of the Cyamudongo study region augmented to some extent with time and were lower in deep layers compared to the soil surface layer. It was found that the land-use types coupled with their management activities with time affected the soil pH in various soil depths. The soil pH at the beginning (2018) of the Cyamudongo Project in various soil depths was lower compared to the recorded values at the end of the study (2019). In AF land use, it was 4.55 and slightly increased to 4.56 at 0-20 cm, 4.37 to 4.53 at 20-40 cm, and 4.30 to 4.45 at 40-60 cm. Besides, the soil pH at the start of the project in CL was gradually increased

in various soil depths from the beginning of the study (2018) to the termination of the study (2019). It was 4.04 and increased to 4.26 at 0–20 cm, 3.94 to 4.28 at 20–40 cm, and 3.86 to 4.17 at 40–60 cm. Likewise, the soil pH values in the NF were decreased from the surface or upper layers toward sub-surface or deeper layers and were 4.27 at 0–20 cm, 4.17 at 20–40 cm, and 3.99 at 40–60 cm. Our experiments are in line with the U. S Department of Agriculture, (2006) that proved that the forest area has lower pH values (more acidic levels) than CL, and transformation of land use from forest to CL can affect the soil pH values within a short period.

The most remarkable result to emerge from the data is that the soil content in terms of OM and its decomposition speed contributed to differences in pH values in various land uses. Hence, the pick values were recorded in AF. Effectively, the implemented AF technologies in the area around Cyamudongo isolated forest influenced the pH increase. Therefore, the mixture of various AF species, which are associated with crops and other growing plants within the system, provides abundant mulches, which contribute to the regulation of soil moisture content, an increase of organic matter, and surface erosion control. Also, the application of fertilizers in the region together with the removal of crop residues for firewood and collecting fodder and mulches for livestock from the farm may contribute to the soil acidity. This result shares a number of similarities with Arévalo-Gardini et al., (2015)

who reported more pH values in AF systems than in the old native secondary forest. Moreover, in agreement with our results, Krstic and Djalovic, (2001) reported the soil pH of forest profiles lower in comparison with meadows and arable lands. Therefore, the leaching of exchangeable bases (Ca^{2+} , Mg^{2+} , K^{1+} , and Na^{1+}) or nutrients from surface to subsurface soils coupled with high rainfall in the study area (1835 mm in 2018 and 1638 mm in 2019) were found also to be the source of low level of pH corresponding to the soil acidic.

Hereafter, the AF practices contributed to the uptake of leached nutrients from the soil deep layers where it is unreachable for the shallow rooting systems of crops. This confirms substantiates previous findings in the literature. The obtained values are barely distinguishable from Emiru and Gebrekidan, (2013) who found that land use and soil depths significantly influence soil pH. The pH variability is due to erosion of base cations, which are replaced by Al^{3+} and H^+ to diminish the soil pH. The application of fertilizers with nitrogen content is another source of soil acidity. Upon its oxidation by soil microbes, it produces strong inorganic acids, which in turn releases H^+ ions to the soil solution that in turn lowers soil pH. McCauley et al., (2017), reported that acidic conditions occur in soil with low buffering capacities (ability to resist pH change), and in regions with higher amounts of precipitation. High precipitation causes the leaching of base-forming cations and the lowering of soil pH.

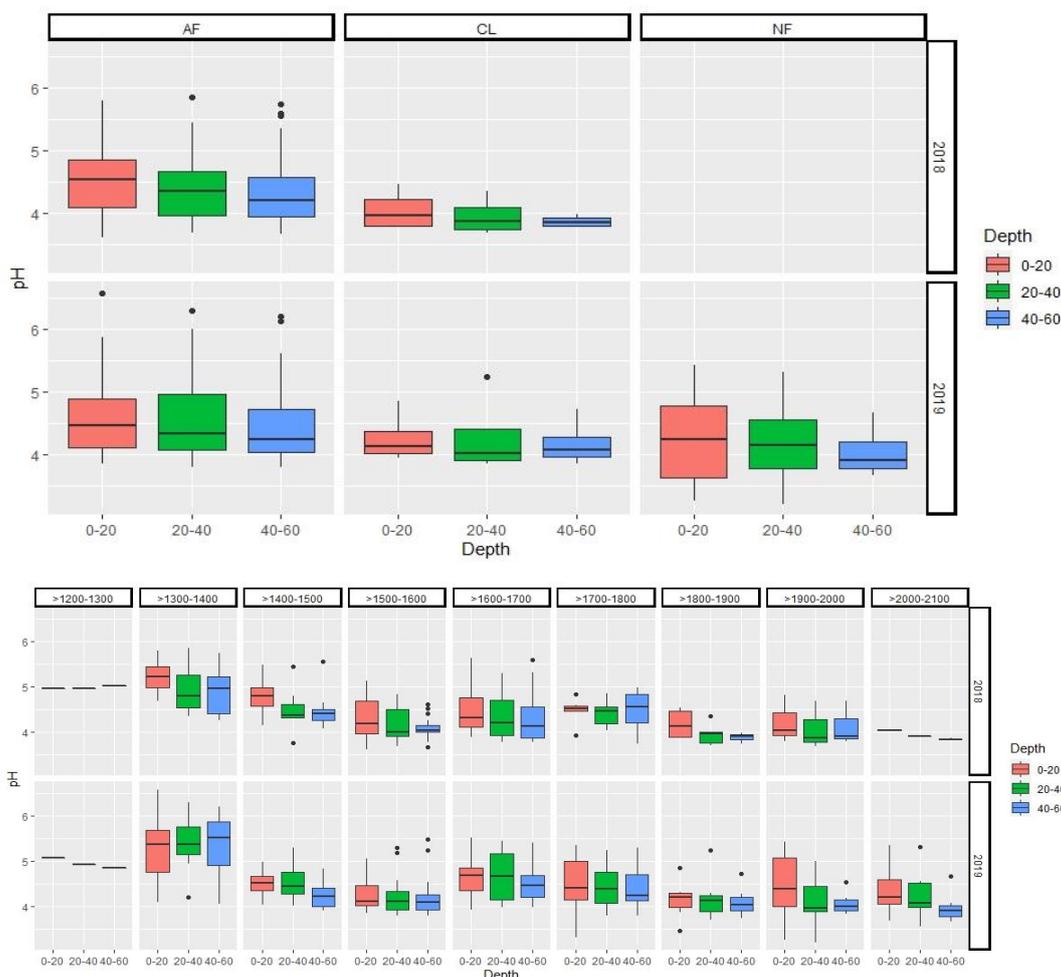


Figure 3. Comparison of soil pH in various sampling depths, land uses, and altitude ranges in different times

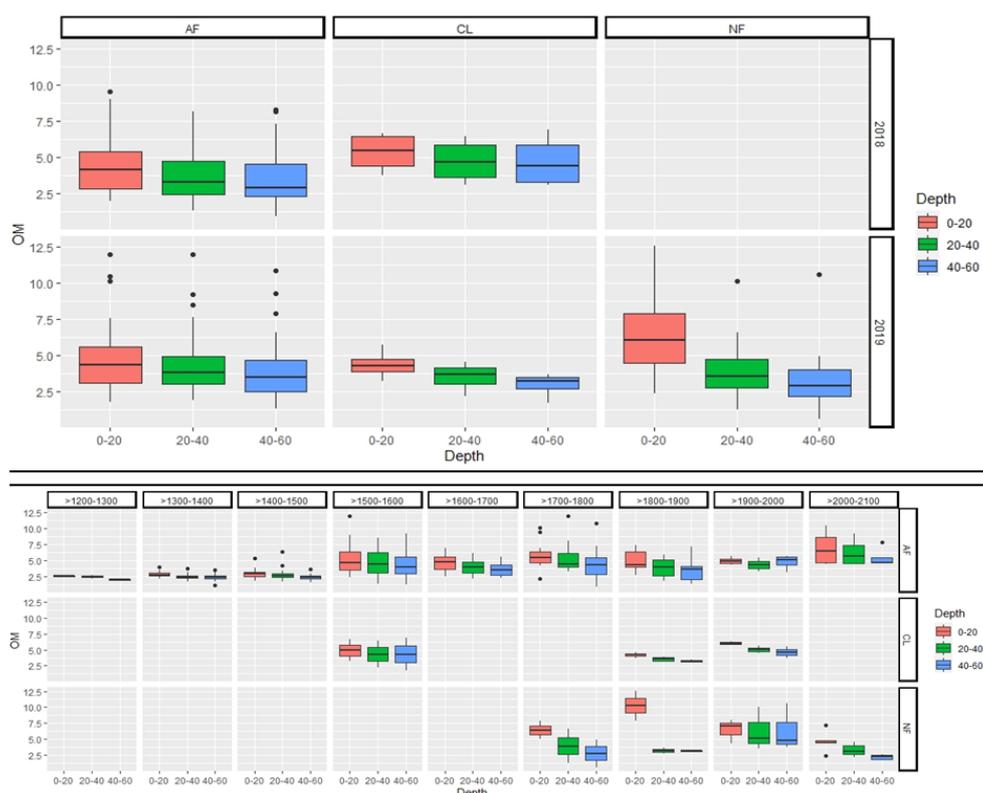


Figure 4. Comparison of soil SOM in various sampling depths, land uses, and altitude ranges in different times

The pH value under NF on the surface soil (0-20) was 4.27. This is consistent with (Lundgren and Nair, 1985) who reported the soil pH belongs between 4.0-4.5 in NF with substantial rain. Taken as a whole, the pH value was acidic. The extent of soil acidification, as measured by a decrease in soil pH, depends mainly on the pH buffering capacity of the soil (Bolan and Hedley, 2003). These results are in the line with those of Lundgren and Nair, (1985) who stated that a pH value < 5 is considered to be strong where Al^{3+} slowly exchange with H^+ and the phenomenon is very serious at H=4.0. These tests revealed that the pH value reduced according to the augmentation of altitude and they were found to be inconstant. It was found that the soil acidity was higher in high altitude ranges (>1800 – 2100 m asl) while it was moderately acidic to slightly acidic in low altitude ranges especially ranging from >1200 to < 1800 m asl (Figure 3). The same results were reported by Vaysse and Lagacherie, (2015) who found that the highest predicted pH values were located in the lowest elevations where alkalization and salinization processes raise the pH. Contrariwise, the smallest pH values were located in the highest parts of the mountains with granitic rocks that produce coarsely textured alterations and are prone to podsolization processes. The biodiversity indicator species including ferns and flowering plants among others can help to describe the soil status of a given area. For example, the ferns indicate eroded and acidic soils (Miccolis et al., 2016). This is in complete agreement with the result of this study where different species of ferns were observed in the area outside Cyamudongo isolated rain forest.

It was found that the soil SOC and SOM were extremely low (<0.40 and <0.70 respectively) to very high (>3.00 and >5.15 respectively) based on interpreting soil test results adapted by Hazelton and Murphy, (2007). The low level of SOC and SOM with extremely low content

found in some areas of the study is probably due to the intensive use of soil by cultivating in all seasons of the year and removing all crop residues after harvesting. Consequently, this leads to declining of both SOC and SOM, which accelerates soil erosion, which in turn contributes to the depletion of nutrients. On the other hand, the SOC and SOM with very high contents in some areas were characterized by good structural condition, high structural stability, and soils probably water repellent. The results showed a significant difference between soil depths as far as SOC (p-value = 0.0013) and SOM (p-value = 0.0013) are concerned. Therefore, the SOC and SOM contents significantly decreased as the soil sampling depth increased for all land uses (Figure 4). Hence, the SOC mean values (in percentage) in AF were 2.62, 2.13, and 0.17 in 0-20 cm, 20-40 cm, and 40-60 cm respectively while the SOM was 4.52, 4.047, and 3.68 respectively in the aforementioned sampling depths. Moreover, the mean values of SOC in CL were 2.8, 2.38, and 2.22 in 0-20 cm, 20-40 cm, and 40-60 cm respectively while SOM was 4.84, 4.11, and 3.83 respectively from the surface, middle, and subsurface soil. Besides, the mean values of SOC in NF were 3.7, 2.39, and 2.02 in 0-20 cm, 20-40 cm, and 40-60 cm respectively whereas the mean values of SOM were 6.3, 4.12, and 3.49 respectively in 0-20 cm, 20-40 cm, and 40-60 cm. By comparing SOM across various land uses, there was no significant difference with p-value = 0.4228. As the percentage changes in SOM content were higher at the surface soil compared to subsoil sampling depths in all land uses, this implies that the surface soil layer is the most biologically active of the soil profiles. The litter on the soil surface resulted from AF practices, crop production and high biomass production from NF caused high biological activity in the topsoil layers. Similarly, Aduagna and

Abegaz, (2015), reported a higher percentage of OM at the surface layer and a small percentage in the subsoil layer across various land uses. Further, (Zhang et al., 2018), stated that the soil organic C and OM contents decreased as the soil depth increased and they were insufficient in most areas with low vegetation cover because of scarce litter in the surface layer. Similarly, Filiz et al., (2013) and reported the mean total N and OM content significantly decreased according to sampling depths. In conformity with this, Lantz et al., (2001) and Sheikh et al., (2009) reported that SOC contents decreased consistently with depths.

Referring to the different times (2018 and 2019), the samples were collected, there was no significant difference for both SOC and SOM with p-value = 0.238. Therefore, one year was not enough to facilitate the accumulation and decomposition of a significant amount of OM on the soil across various land uses. The OM value significantly increased with the increase of altitude even though it was not consistent and consequently the soil OM lower values were found in low altitude levels (>1200-1500 masl) while the high values were found in high altitude ranges (>1500 – 2100 m asl) (Figure 4). In connection with this, the OM is highly accumulated in high altitudes ranges than in low altitude ranges of the study area.

Generally, a large part of both CL and AF land uses are located in low altitude ranges while the NF is only found in high elevations (>1800 m asl). The high soil OM in NF is due to high rainfall of Cyamudongo isolated rain forest (1835 mm in 2018 and 1638 in 2019), which promotes plant growth; cooler temperature, and high soil acidity of the area, which could decrease the rate of decomposition and mineralization of soil OM. Besides, the cooler

temperature is in the relation to higher altitude ranges. However, the lower accumulation of soil OM in low altitude ranges might be attributed to the high temperature and frequent tillage activities which prevent the accumulation of OM. Usually, lower altitudes areas are having a higher temperature than areas with high altitudes (Kidanemariam et al., 2012).

The N mean value decreased with the increase of soil depth. The recorded percentage of N mean values are 0.23, 0.20, and 0.12 in 0-20 cm, 20-40 cm, and 40-60 cm respectively. The averaged N mean value in all soil depths is 0.20. For soil total Nitrogen, there was a significant difference in N among soil depths, land uses, altitude ranges with p-value = 2.159e-05, p-value = 0.01567 and p-value < 2.2e-16 respectively. Besides, the result shows that there is no significant change (p-value = 0.2725) for N percentage with a one-year time interval. The N percentage decreased significantly, as the soil sampling depth increases across various land uses whereas it was significantly increased as the altitude level increased (Figure 5). The substantial amount of precipitation of the study area coupled with the low temperature in high altitude may decrease the soil organic matter decomposition. Consequently, the percentage of the total Nitrogen was higher in the high-altitude ranges than in the lower altitude ranges. These results are in the line with Filiz et al. (2013), who reported the total N content increased along the altitudinal gradient and it is likely that differences in soil nitrogen storage were also caused by differences in decomposition and nitrogen turnover rates. It was also reported that the nitrogen increased with increasing altitude (S. Kumar et al., 2010).

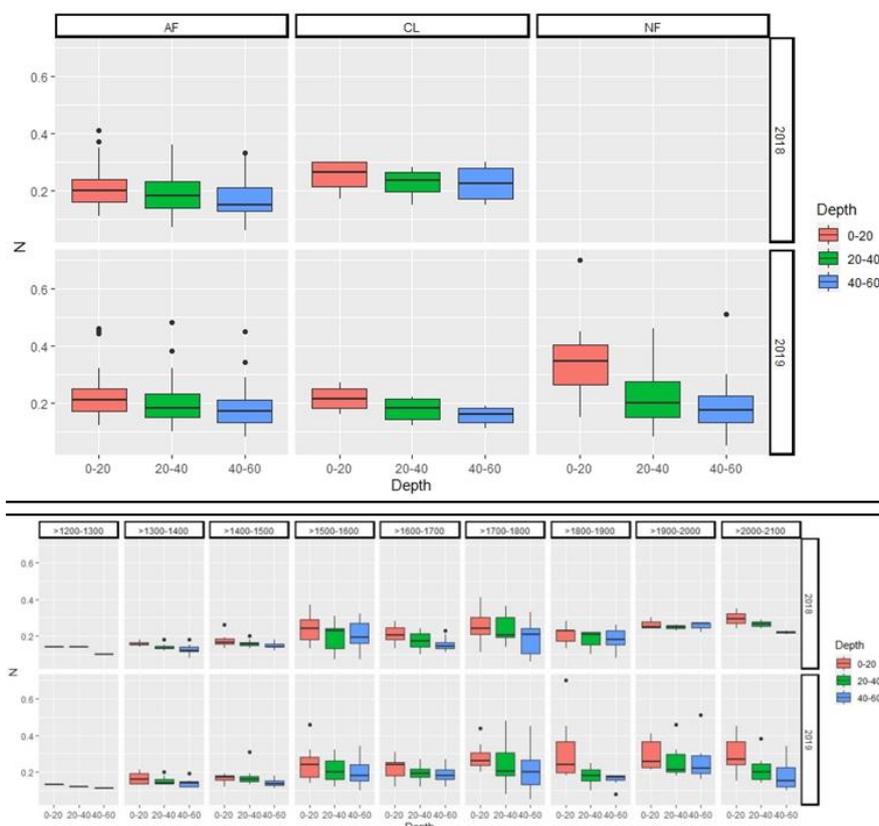


Figure 5. Comparison of soil total N in various sampling depths, land uses, and altitude ranges in different times

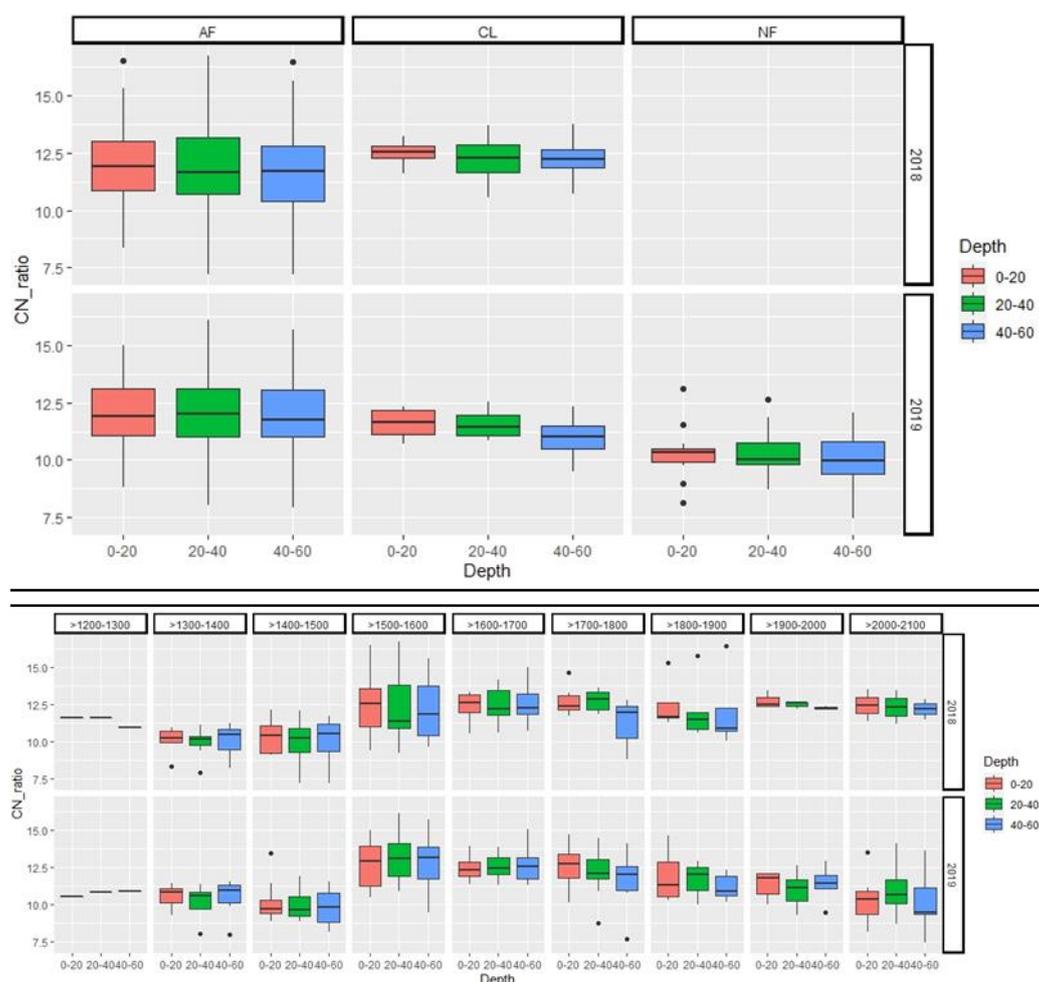


Figure 6. Evaluation of soil C: N ratio in soil depths, land use, and altitude range with time

The mean N value in the study area was rated from medium (0.15–0.25) to high (0.25–0.50) according to the soil test interpreting results reported by Hazelton and Murphy, (2007). The mean N was tested in different soil sampling depths, land uses, altitudes range for different times of data collection. The N mean value was higher in NF, followed by CL and AF. Starting with soil depths in AF, the mean N value was 0.21, 0.19, and 0.17 in 0–20 cm, 20–40 cm, and 40–60 cm respectively. The N means value in CL was 0.23, 0.2, and 0.19 respectively from the top to down of the soil depth. The N means value in NF was 0.4, 0.22, and 0.19 in the surface, medium, and soil subsurface. The high amount of total N found in the natural forestland use is in the relation to the high amount of OM recorded in the natural forest especially on the soil surface layer. As the percentage of N increased with the increase of altitude, this also indicates the positive relationship between N values with altitudinal gradient. In forestland, a large number of mulches on the soil surface produced by the mixture of plants, trees, shrubs contribute significantly to the high amount of N at the soil surface. As the decomposition of OM in the high altitude coupled with low temperature and a substantial amount of rainfall contributed significantly to the difference of tested N in various soil depths. It may take a long time beyond a one-year interval to facilitate a significant change of N and OM in similar environmental conditions. The continuous cropping of the whole year in

AF and CL resulted from a small percentage of total N compared to the recorded N in NF.

These results are consistent with Demiss and Beyene, (2010) who reported the high amount of organic C and total N at the soil surface that declined with soil depths. In their study, the total N on the soil surface along altitudinal gradient had also a comparable tendency of OM. Similarly, Filiz et al. (2013), reported that the OM and Total N decreased along with the soil depth while they increased along the altitudinal gradient. Emiru and Gebrekidan, (2013), reported total N contents of soils demonstrated significant variation between land uses ($P \leq 0.01$), soil layers ($P \leq 0.01$), and interaction between the two factors ($P \leq 0.01$). Total nitrogen content declined with a shift of land uses from the natural forest into agricultural fields, and with increasing soil depth from 0–20 cm to 20–40 cm.

The C: N ratio of the study area was rated from very low (<10) to low (10–15) according to the soil test interpreting results reported by Hazelton and Murphy (2007). They further interpreted the C: N ratio < 25 indicates that the decomposition of OM may proceed at the maximum rate possible under environmental conditions. This is in complete agreement with Jiang et al. (2019), who stated that the C: N lower than 25:1 indicates that there is enough percentage of C and N in soil that is important to sustain the soil productivity and nutrient availability. No significant difference was observed between soil depths (p-value = 0.6425), land use (p-value = 0.6425) and altitude

ranges (p -value = 0.2725) in various periods of data collection as with regard to C: N ratio. Further, the analysis tests showed a significant difference in C: N ratio for different altitudes ranges and land use with p -value < 2.2e-16 and p -value = 2.099e-08 separately. The C: N ratio mean values on the soil surface layer (0-20 cm) were 11.95, 12.03, and 10.3 in AF, CL, and NF respectively. Also, on the medium soil layer (20-40 cm), its mean values were 11.91, 11.89, and 10.3 in AF, CL, and NF distinctly. Moreover, in the dipper sampling soil layer (40-60 cm), the mean values in AF, CL, and NF were 11.77, 11.6, and 9.9 respectively.

Generally speaking, the C: N ratio declined with the augmentation of soil depths crosswise land uses. Kafle (2019) noted that C: N ratio of the soil increased with the increase of soil depths. The result of my study to not support his observation in the fact that the trend of the C: N ratio is different from our current findings. The high mean values were recorded in CL followed by AF and NF (Figure 6). This is in good agreement with Toru and Kibret, (2019) who reported the pick values in terms of soil C: N ratio in CL and compared AF and NF soils. Fetene and Amara, (2018) reported a small amount of C: N ratio in uncultivated areas than in cropped areas. On one hand, it agrees with the results of Emiru and Gebrekidan, (2013) where they found the numerical values for land uses that

are highest for cultivated soils and lowest for forest soils, which can be due to the rapid loss of N (the denominator) in the former. On the other hand, it disagrees in the way that the variation in C: N ratios between land use did not reveal significant ($P > 0.05$) differences but varied across soil depth significantly ($P \leq 0.05$).

It was found that the observed $\text{NO}_3^- + \text{NO}_2^-$ is between 9.8 and 21.24 mg/Kg. This range falls in the 100% (7–15 mg/Kg) to 60% (16–22 mg/Kg) probability of a profitable response to nitrogen fertilizer based on soil test interpreting results adapted by Hazelton and Murphy, (2007) understudy carried out by Holford and Doyle (1992). Their study was about yield responses and nitrogen fertilizer requirements of wheat about soil nitrate levels at various depths. Furthermore, the recorded $\text{NO}_3^- + \text{NO}_2^-$ was ranked from low (<10), medium (10-20) to high (20-30) about the soil interpretation guide of Marx and Hart (1999). Eventually, they were classified with the current information as deficient for most crops (<10 ppm), Low (10-20 ppm), and moderate (20-30 ppm) (Flynn, 2015). The $\text{NO}_3^- + \text{NO}_2^-$ shows a significant difference for both sampling depths and altitude ranges with p -value = 5.165e-08 and P -value = 1.675e-05 respectively. No significant difference highlighted between land uses and data collection periods with P -value = 0.4364 and P -value = 0.08637.

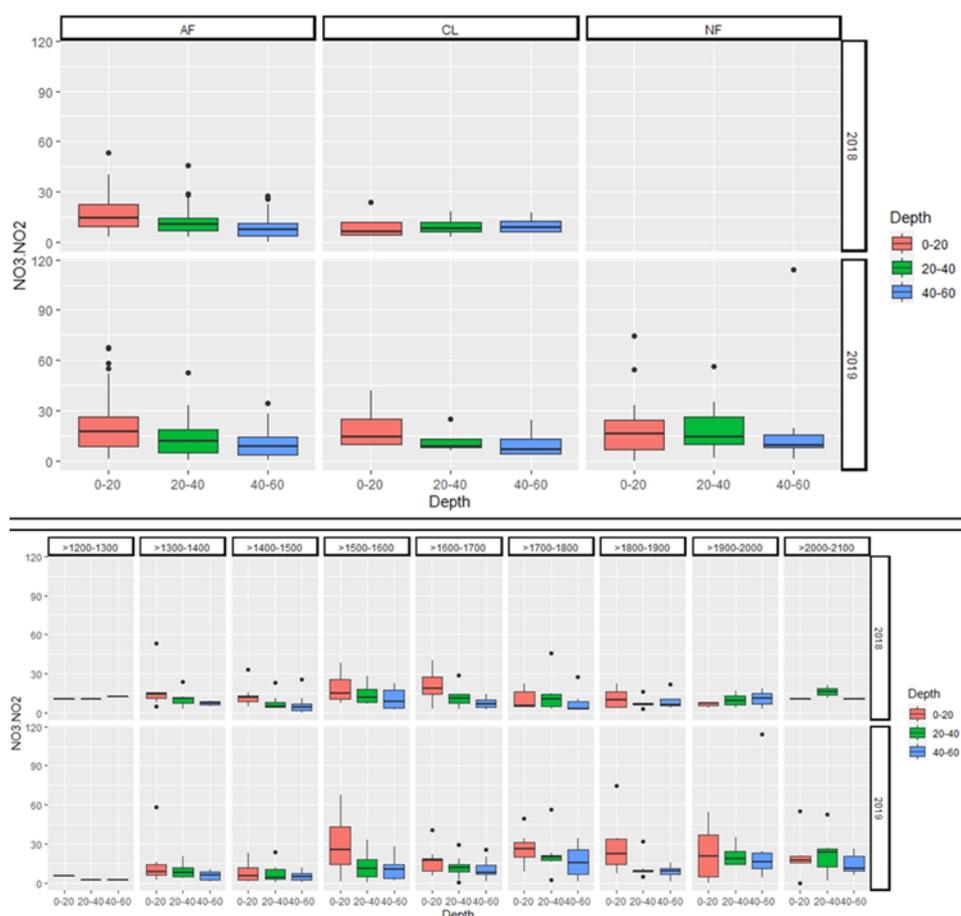


Figure 7. Comparison of soil $\text{NO}_3^- + \text{NO}_2^-$ ratio in various sampling depths, land uses, and altitude ranges in different times

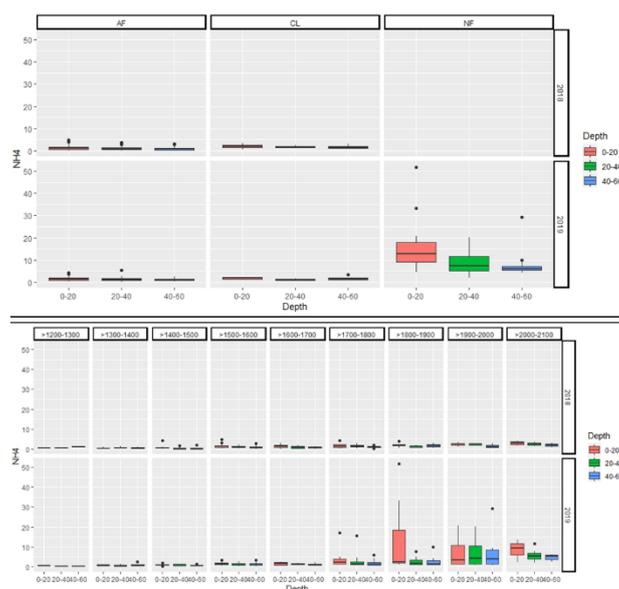


Figure 8. Assessment of soil NH_4^+ ratio in soil depths, land uses, and altitude ranges with time

The $\text{NO}_3^- + \text{NO}_2^-$ mean values in mg/Kg across various soil depths in AF land use were 18.94 (0-20 cm), 12.72 (20-40 cm), and 9.8 (40-60 cm). In CL, they were 15.07, 10.81, and 13.58. In NF, they were 21.24, 19.30, and 18.82. The $\text{NO}_3^- + \text{NO}_2^-$ mean values decreased as the soil depth increased in all land uses. Generally, the high mean values are ranked in the following order: $\text{NF} > \text{AF} > \text{CL}$ (Figure 7). This result concurs with Xue et al., (2013). In their study, significant effects were observed in the concentration of soil nitrate-nitrogen ($\text{NO}_3^- \text{--N}$), depending on soil profile depths. Compared to the natural grassland areas, the soil nitrate-nitrogen contents decreased in the manmade grassland, abandoned farmland, farmland, and orchard.

In Cyamudongo, the land-use conversion and variation in altitude patterns marked with high slopes associated with erosion result in a high variation among N concentrations. In general, soil nitrate-N is removed from the upper layers by leaching after rainfall; indeed, the soil nitrate-N in the 0-20 cm layer was significantly greater than in the 20-40 cm layer. Nitrate is highly reached from the soil with high rainfall or excessive irrigation (Marx and Hart, 1999). The recorded amount of $\text{NO}_3^- \text{--N}$ in the Cyamudongo study area is due to the sampled depth, intensive rainfall, and high elevations remarkable in the region. Nitrate-N, however, is the form most common in arable soils and is a measure of readily available nitrogen for plant use. Because $\text{NO}_3^- \text{--N}$ is highly soluble and has a negative charge, it is subject to leaching in all soils, but especially in coarse- to medium-textured soils (Flynn, 2015). Plant available form of nitrogen is Nitrate and ammonium. Soil concentration of Nitrate and ammonium depend on biological activities and therefore fluctuate in the conditions such as temperature and soil moisture (Marx and Hart, 1999).

Nitrate-N (NO_3^-) is a negatively charged anion and is therefore not held by the soil but remains highly mobile in the soil solution. This mobility means that nitrate-N is readily available for plant uptake, but (in high rainfall events and free-draining soils) is more easily leached out of reach of the plant root system (Botta, 2016).

The NH_4^+ shows a significant difference for sampling depths, land uses, altitude ranges and times of data collection with p-value = 0.0083, p-value < 2.2e-16, p-value < 2.2e-16 and p-value = 4.531e-08 correspondingly. According to Marx and Hart (1999), the observed amount of Ammonium-nitrogen of the study area were in the range of < 10 (typical concentration) and > 10 ppm (occur in the cold or extremely wet soils). The NH_4^+ average values were computed in targeted land uses. For AF, the results in mg/Kg were 1.46, 1.16, and 1.005 separately in 0-20 cm, 20-40 cm, and 40-60 cm. Thereafter, with CL the mean values were 1.91, 1.49, and 1.23 chronologically in the consistent soil depths. Finally, for NF, they were 16.62, 8.61, and 8.1 consistently with soil depth. The highest values were observed on the surface layer and the mean value of NH_4^+ increased significantly and consistently with the increase of altitude. The observed ammonium nitrate in the high altitude is concerning the high amount of OM and N percentage recorded in the high altitudes, which are dominated by the NF land use where the high precipitation is dominant. The precipitation usually distributed in the whole year advantaged microbial processes that allowed greater ammonium mineralization.

It was observed that the pick averages were in NF, followed by CL and AF, and declined as the soil depth augmented (Figure 8). Our results agree with the findings of Xue et al., (2013) who found the significant effects that were observed for the concentrations of soil ammonium nitrogen ($\text{NH}_4^+ \text{--N}$), depending on the different land uses and soil profile depths. Compared to the natural grassland areas, the soil nitrate-nitrogen contents decreased in the manmade grassland, abandoned farmland, farmland, and orchard. In their study, the surface layer exhibited the greatest soil ammonium-nitrogen concentration in various land uses. This result concurs with Xue et al., (2013), In their study, significant effects were observed in the concentration of soil nitrate-nitrogen ($\text{NO}_3^- \text{--N}$), depending on the different land uses and soil profile depths. Compared to the natural grassland areas, the soil nitrate-nitrogen contents decreased in the manmade grassland, abandoned farmland, farmland, and orchard.

The NH_4^+ of the study area was significantly highly influenced by various factors including soil depth, land use, altitude, and precipitation. Unlike nitrate-N, ammonium-N (NH_4^+ is a positively charged cation and can be chemically bonded onto the (negatively charged) surfaces of clays and organic matter. Agronomists use levels of ammonium-N on soil tests to indicate how much N is likely to become available (Botta, 2016). Ammonium-N does not accumulate in soil due to the effects of soil temperature and moisture that favor the conversion of NH_4^+ N to NO_3^- N (Flynn, 2015).

Mainly, the soil PO_4^{3-} was found to be very low (<5) to very high (17-25) in accordance to Hazelton and Murphy, (2007). Generally, the minimum value was 0.1 mg/L whereas the maximum value was 19.62 mg/L and the averaged mean value was 2.1 mg/L considering all the records made for soil depths, land uses, altitude ranges, and times of the data collection. The soil PO_4^{3-} average values reduced with the rise of soil depth (Figure 9): 0-20 cm (2.78 mg/L), 20-40 cm (1.84 mg/L), and 40-60 cm (1.71 mg/L), and the difference was significant. Our results agree with Emiru and Gebrekidan, (2013) who reported the high soil PO_4^{3-} value on surface soil while decreased with the increase of soil depth though not statistically significant. This result is shown a significant difference between land uses with a peak average in NF (2.98 mg/L), followed by AF (2.12 mg/L) and CL (0.59 mg/L). As anticipated, this result demonstrates the impact of land-use change from NF to CL reduced significantly the P availability compared to AF. The tests did not confirm any significant difference between NF and AF ($P > 0.05$). On the other hand, Bizuhoraho et al., (2018) reported the highest AP in the farmland with the value of 84 ppm, followed by cultivated land with a value of 76 ppm, and finally, the lowest AP was found in the forested land with a value of 70 ppm.

Climatic conditions, such as rainfall and air temperature, and site conditions including soil moisture, aeration, and salinity affect the rate of mineralization of P because of the decomposition of organic matter. The soil pH value of 6 to 7.5 is perfect for P to support the vegetation growth. Values of less than 5.5 and 7.5-to 8.5 limit availability of P because of fixation by aluminum, iron, or calcium, which commonly are associated with soil parent material (USDA, 2006). The small amount of recorded P is due to the experienced high amount of rainfall in the Cyamudongo area that causes the loss of P at the soil surface through leaching. This is consistent with Zhang et al., (2018), who informed the loss of P caused by precipitation. The overall pH means the value of the study area was low and strongly acidic (4.41) and this value limits the availability of soil available P. The pH level of the study area especially in AF and cropland land use should be increased and maintained at a range of 5.5–7.2 for optimal availability and uptake by plants (Cerozi and Fitzsimmons, 2016).

The results showed a significant difference between altitude ranges ($P > 0.05$) and the averaged mean value was 2.1 mg/L. The available P has neither decreased nor increased with the altitudinal gradient.

Initially, the CEC was estimated by summing the exchangeable base cations or alkaline-forming (or base) cations (Calcium (Ca^{2+}), Magnesium (Mg^{2+}), Potassium (K^+), and Sodium (Na^+) ('CEC by bases') (Botta, 2016). The Effective Cation Exchange Capacity ECEC (base and acid cations) was calculated by considering the Al^{3+} . Aluminum is a predominant cation in many soils and can be a critical variable in establishing ECEC values. For ECEC determinations it is not necessary to differentiate between exchangeable Al^{3+} and H^+ (Robertson and Ellis, 1999).

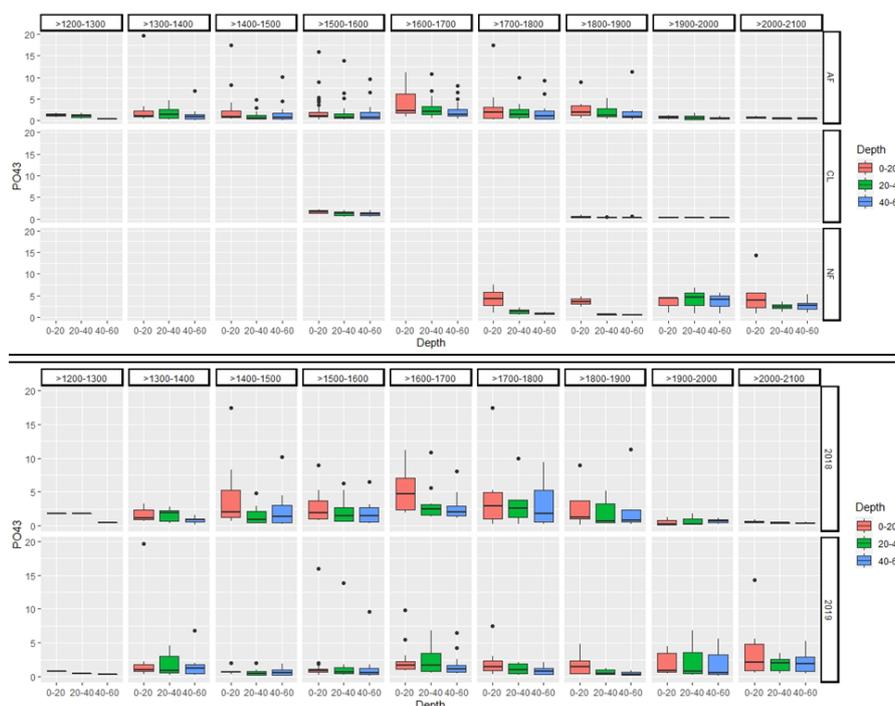


Figure 9. Comparison of soil PO_4^{3-} ratio in various sampling depths, land uses, and altitude ranges in different times

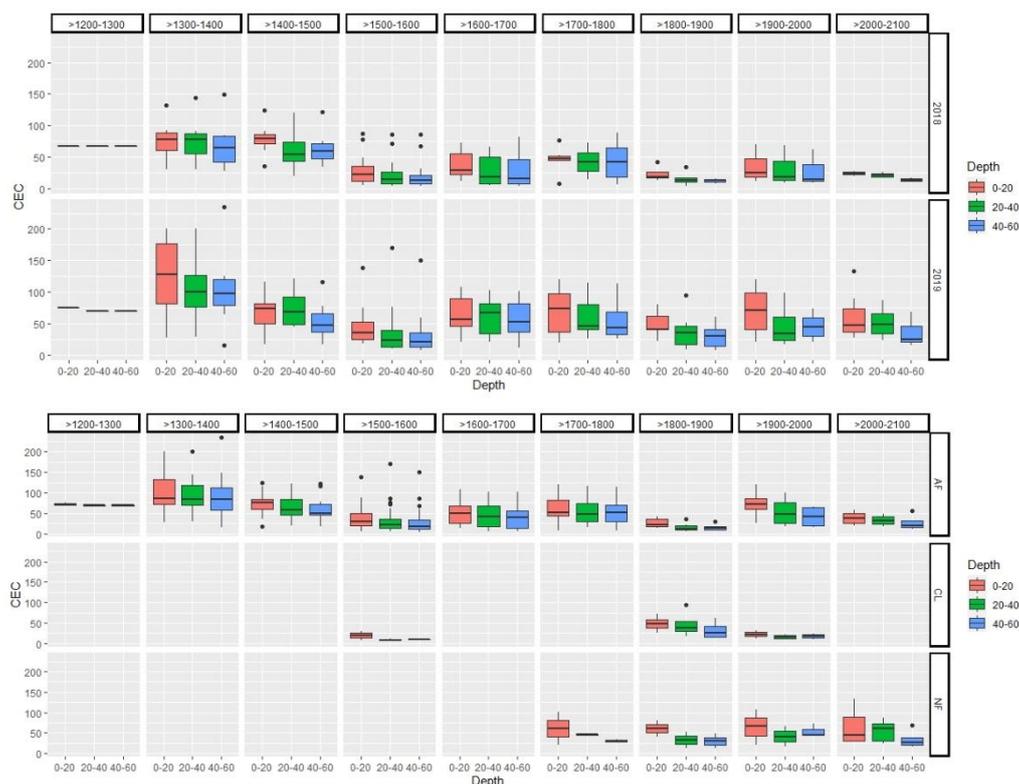


Figure 10. Evaluation of soil PO₄³⁻ in sampling depths, land uses, and altitude ranges with time

Therefore, the CEC of the study area was ranked as very low (<6 cmol (+)/kg) to very high (>40 cmol (+)/kg) according to the interpreting soil results of Hazelton and Murphy, (2007). The general average was 49.23 and it is an indicator of very high CEC of the study area. The lowest minimum value was 3.7 mg/L while the highest value was 234.76 mg/L. The CEC mean value was significantly decreased with the increase of soil depth (Figure 10). Our results concur with Adugna and Abegaz, (2015) who found the decrease of CEC with the increase of soil depth. The CEC increased significantly with increasing years. This last is in agreement with Arévalo-Gardini et al., (2015) who reported the increase of CEC with increasing years. The CEC was also significantly influenced by land uses (P<0.05). The tests revealed a significant difference between AF and CL, CL and NF. No significant difference was detected between AF and NF. The CEC high values were recorded in AF (50.7 mg/L), followed by NF (49.2 mg/L) and CL (28.9 mg/L). The high CEC value in AF especially on the surface layer is associated with OM. Our results conform with Sharma et al. (2009) who found that the CEC and organic carbon (OC) were significantly influenced by the land-use systems and AF system resulted in the highest pH (7.5), CEC (13.6 cmol/ kg), and organic carbon (C) content (9.6 g/ kg). The overall ECEC mean value was 56.8 mg/L.

The general pH values were low and ranked as strongly acidic (pH = 4.41). Therefore, soils with low pH should be tested for exchangeable Al as a measure of potential Al toxicity (Landon, 2017). The Al³⁺ coupled with substantial rainfall were found to be the main source of soil acidity of the study area. The Al³⁺ mean value was 6.9 and is rated as high according to Pekin, (2013). Our results agree with other researchers' findings. Initially, Botta (2016) reported that in acid soils the positive cations such as H and

aluminum replace the soil basic cations such as calcium, magnesium, and potassium. This can be especially significant in high rainfall environments (greater than 600 mm) due to the potential leaching of the basic cations (Ca²⁺, Mg²⁺, K¹⁺). Further, Landon, (2017), stated that for acidic soils (pH < 5.5), there are possibly Al toxicity and excess Co, Cu, Fe, Mn, Zn; and deficient in Ca, K, Mg, Mo, P, S. Al ions are released from clay lattices at pH values below about 5.5 and become established on the clay complex. Therefore, as a principle, "in soils of low pH (<5.5) it is not the hydrogen ions (H⁺) that operate as a direct constraint to plant productivity, but rather the abundance of toxic cations, primarily Al³⁺ and to a lesser extent Mn²⁺" (Marschner, 1986). In tropical soils, the exchangeable acidic cations in soils between pH 3 and 5.5 values are only made by Al (Okalebo et al., 2002). The Al saturation in the Cyamudongo study area was high (63.13%) which may prevent the soil productivity as the recorded available P and organic C were low.

Figure 12 shows how the pH is correlated with, CEC and alkaline-forming cations in various land use including AF, CL, and NF. As a result, the pH was very strongly correlated with CEC, Mg, and Ca in CL whereas it was strongly correlated in both AF and NF except for Mg, which was moderately correlated in AF. Furthermore, its correlation with K was strong in CL, moderate in AF while it was weak in NF. Finally, the pH correlation with Na was weak in both AF and CL whereas it was negligible in NF (Figure 12).

The tests showed that the soil CEC was strongly correlated with soil pH in various soil depths. Soil pH is frequently called the master soil variable because it affects soil productivity (Minasny et al., 2016) and (Botta, 2016). As the pH increases, the CEC tends to increase.

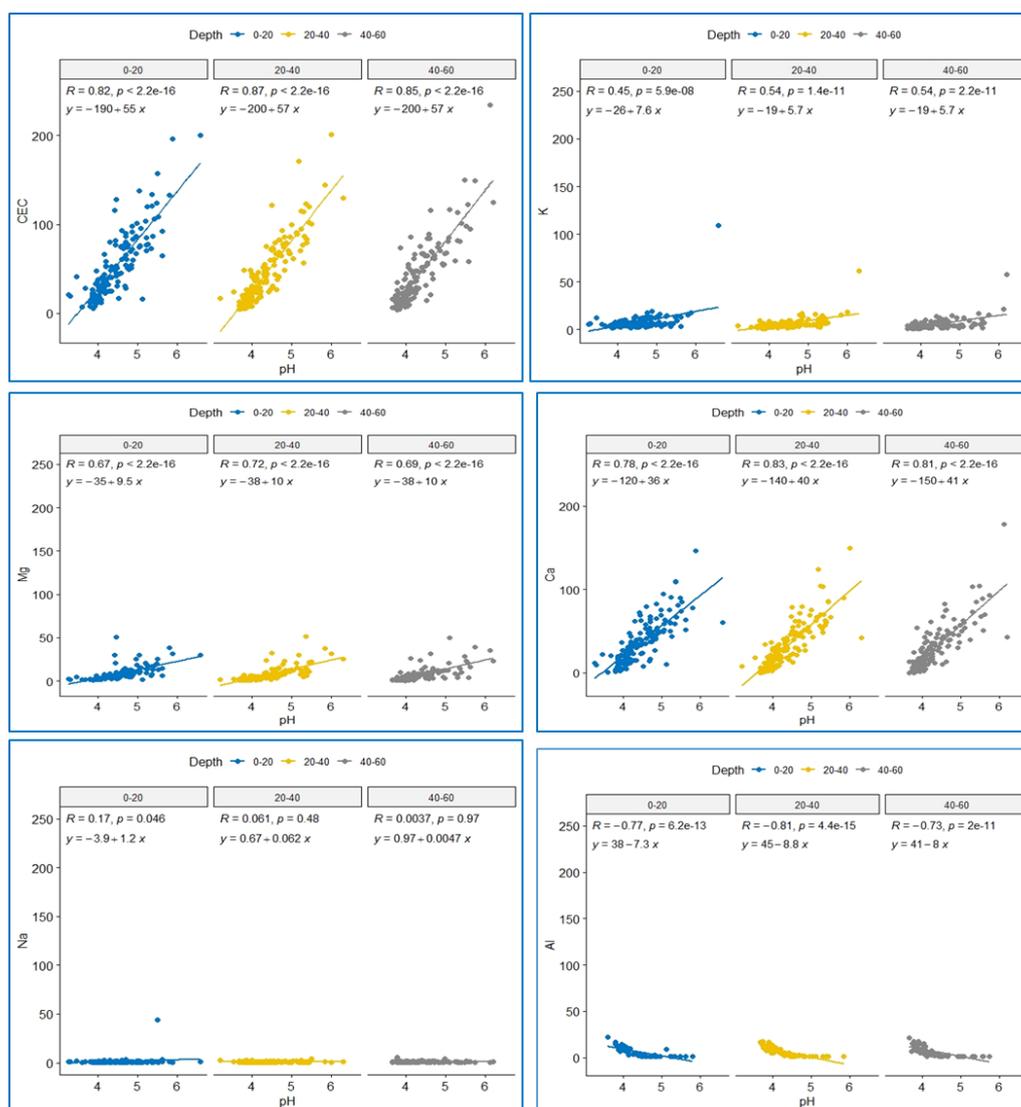


Figure 11. Relationship between soil pH, CEC, and exchangeable cations in different sampling depths

Our findings coincide with the correlations reported by (omašić et al., (2013) where they found the correlation coefficient between base saturation (V %) and pH for all soils was $r=0.79$ that is a strong correlation for the studied soils according to the used correlation intensity scale used for our study. As the pH increases, the CEC tends to increase. Our findings coincide with the correlations reported by Tomašić et al., (2013) where they found the correlation coefficient between base saturation (V %) and pH for all soils was $r=0.79$ that is a strong correlation for the studied soils according to the used correlation intensity scale used for our study. The observed correlation coefficients were similar to those of Muraoka, (2001) who reported the positive correlations between the values of P, Ca^{2+} , Mg^{2+} , K^+ , SB, CEC and V%, and soil pH, and a negative correlation between aluminum saturation (m%), showing the importance of soil reaction on soil fertility and the conditions for crop production.

The Al was negatively strongly correlated with pH in all soil depths. It meant that as the pH decreases, the Al increases. The observed correlation coefficients were similar to those of Muraoka, (2001) who reported the positive correlations between the values of P, Ca^{2+} , Mg^{2+} , K^+ , SB, CEC and V%, and soil pH, and a negative

correlation between aluminum saturation (m%), showing the importance of soil reaction on soil fertility and the conditions for crop production. Therefore, the leaching of exchangeable bases (Ca^{2+} , Mg^{2+} , K^{1+} and Na^{1+}) or nutrients from surface to subsurface soils coupled with high rainfall in the study area (1835 mm in 2018 and 1638 in 2019) were identified to be the main sources of high soil acidity in the area around Cyamudongo isolated rain forest. Another possible reason is the application of nitrogen fertilizers, which result in soil acidification. As soil pH decreases, aluminum (Al) is solubilized and the proportion of phytotoxic aluminum ions increases in the soil solution (Krstic and Djalovic, 2001). Strongly acidic Al can have Ca, Mg, and K deficiency (due to possible leaching) which affects the soil's biological function. Several factors contribute to acid soil toxicity depending on soil composition. In acid soils with high mineral content, the primary factor limiting plant growth is Al toxicity. The Al released from soil minerals under acid conditions occurs as $Al(OH)^{2+}$, $Al(OH)$, and $Al(H_2O)^{3+}$, the latter commonly referred to as Al (Kinraide, 1991). He further stated that, for most agriculturally important plants, Al ions rapidly inhibit root growth at micromolar concentration.

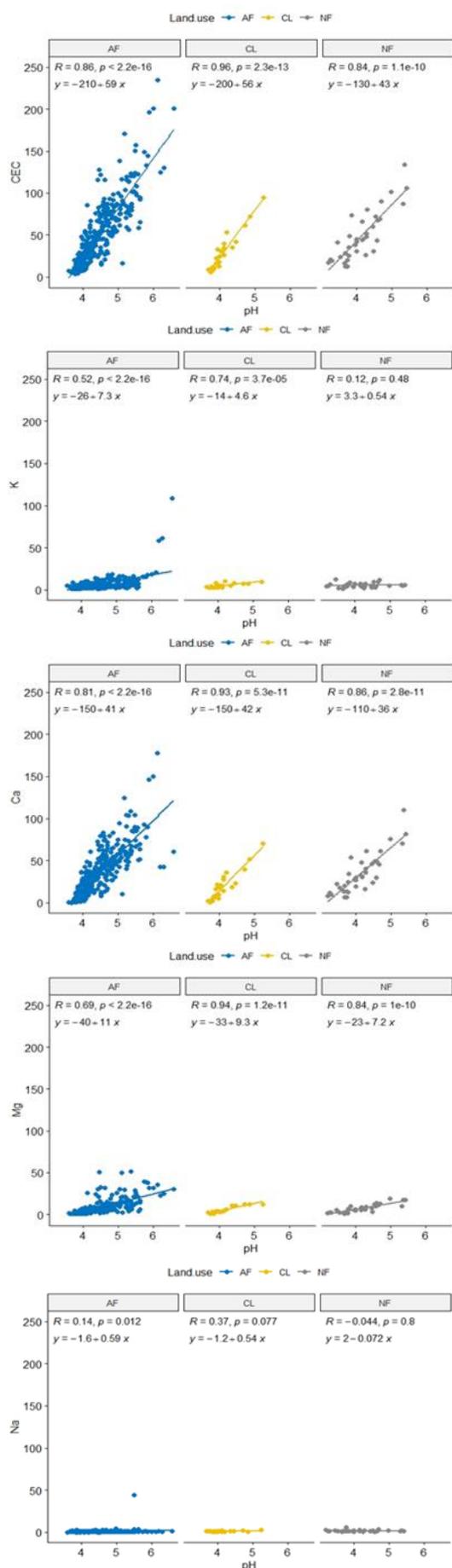


Figure 12. Relationship between soil pH, CEC, and alkaline-forming cations in different land uses.

The values of CEC and base exchangeable cations (Ca^{2+} , Mg^{2+} , K^+ , and Na^+) significantly vary depending on soil type and their horizons, which can be seen in the obtained values of CEC and each base cation. Cation exchange capacity is under the influence of numerous chemical and physical parameters of soil, which, with climate and relief, influence its values (Tomašić et al., 2013). The particularity of Al was only one element to be strongly correlated with CEC compared to other elements. It is different from K, Mg, Ca, and Mg as it was found to increase with the pH decrease while the others increase with pH increases (Figure 11). Its correlation with pH was found to be negative with a very strong correlation in >1200-1300 m and >1900-200 m, moderate correlation in >1300-1400 m, and strong correlation in all other remaining altitude ranges. The topography can be the basis to characterize and describe the soil productivity of a particular area (Jiang et al., 2019). Elevation, or vertical distance, represents the integration of geographic distance and a variety of abiotic and biotic factors including light, temperature, water, and vegetation that change along the elevation (B. Zhang et al., 2019). The 8°C fluctuations at ground level, reducing to 4°C at 200 m and less than 2°C at 800 m (THOM, 1975). A progressive decrease in the temperature of the soil can happen with the augmentation of altitude (Jiang et al., 2019). The soil pH was correlated with other nutrients, as it is an important indicator of soil health. It affects crop yields, crop suitability, plant nutrient availability, and soil microorganism activity and influences key soil processes. The test revealed that the recorded soil pH means value across the study area is 4.2, which is very strongly acidic. Figure 11 illustrates the association among various selected soil variables such as pH, CEC, and exchangeable cations in depths using regression analysis to determine how the soil has been cared for. The regression coefficients, lines, and p-values were provided. The results were interpreted about appropriate use and interpretation of correlation coefficients described by (Schober et al., 2018). The tests showed that the soil CEC was strongly correlated with soil pH in various soil depths. The tests highlighted that the CEC tends to increase with the pH increase. The K was moderately positively correlated with pH in different soil depths. Mg was moderately positively correlated with pH in 0-20 cm and 40-60 cm soil depths whereas it was strongly correlated with pH in 20-40 soil depth. The Ca was strongly correlated with pH in various soil depths. There was a negligible correlation between Na and pH in 40-60 cm soil depth found in various land uses whereas the correlation was a week for 0-20 cm and 20-40 cm soil depths. The Al was negatively strongly correlated with pH in all soil depths. It meant that as the pH decreases, the AL increases.

Conclusion

Our work has led us to the conclusion that sustainable AF can contribute to the improvement of soil properties. The tests revealed that the soil pH, C, N, C: N ratio, OM, NH_4^+ , $\text{NO}_3^- + \text{NO}_2^-$, PO_4^{3-} , and CEC were significant in different soil depths. The pH, N, C: N ratio, CEC, NH_4^+ , PO_4^{3-} , and Al^{3+} showed a significant difference across land uses whereas the C and $\text{NO}_3^- + \text{NO}_2^-$ did not show any statistical difference. All tested chemical elements showed

a statistical difference as far as altitude ranges are concerned. The only NH_4^+ , PO_4^{3-} , and CEC showed significant differences with time whereas all other remaining chemical elements did not show any statistical significance.

These results seem likely to confirm the hypothesis stating that there is a significant difference of selected soil properties throughout the time in the study area especially for NH_4^+ , PO_4^{3-} , and CEC. Contrary to expectations, this assumption was rejected for pH, C, C: N ratio, OM, and $\text{NO}_3^- + \text{NO}_2^-$. As anticipated, this hypothesis was accepted also for all tested elements in different altitude ranges. The hypothesis was further accepted for various nutrients in different soil depths except for soil N which was not changed significantly. It may be assumed that the pH, N, C: N ratio, CEC, NH_4^+ , PO_4^{3-} , and Al_3^+ significantly change with different land uses which is not supported for the C and $\text{NO}_3^- + \text{NO}_2^-$. The pH level in AF and CL should be increased and maintained at a range of 5.5-7.2 for optimal availability and uptake by plants.

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